Integrated Automotive Exhaust Engineering - Uncertainty Management

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Abstract

The global automotive industry has entered a stagnating period. Automotive OEMs and their tier suppliers are struggling for business growth. One of the most important strategies is to improve the engineering efficiency in the product development process. The engineering uncertainties have been identified as the main obstacles in the Lean Engineering practices.

This study will be focused on the engineering development process of ArvinMeritor Emission Technologies. The lean engineering principles and techniques are applied to the current product development process. The Value Stream Mapping and Analysis method is used to identify the information flow inside the current engineering process. Based on the value stream map, the uncertainties at various development stages in the process are identified. The Design Structure Matrix is used to identify any unplanned design iteration, which results in lower engineering efficiency. The House of Quality is used to prioritize the importance of the iterations. The suggested excel program can effectively evaluate the effect of task duration, probability, impact and learning curve assumption.

In order to quantitatively predict the effects of the uncertainties, a System Dynamic model is specifically developed for the current engineering of Emission Technologies.

The results clearly indicate the control factors for on-time delivery, efficient resource allocation, and cost reduction.

This study has integrated the techniques from system engineering, system project management, and system dynamics. An improved automotive exhaust engineering process is proposed.

Acknowledgments

The authors welcome the opportunity to acknowledge several people who have been instrumental in the completion of this thesis. Paramount among these individuals is Dr. Whitney, whose guidance and technical contributions have had a significant impact on the completeness of our research. Special thanks are due to Ms. Gail Guynn, Mr. David Leehaug, Mr. Kenny Cook, Mr. Anthony Hicks, Mr. Larry Antle, Mr. Frank Padalik, Mr. John Laswell, and Mr. John Grace for their invaluable support and research contributions.

Finally, we thank ArvinMeritor, Inc., for the sponsorship of our study.

Submitted in June, 2006

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Chapter 1 Introduction

1.1 Motivation For the Research

The US automotive OEMs and tier suppliers are experiencing a most difficult period. They are losing global market share. Automotive emission control is becoming more stringent. Raw material cost is increasing. In order to get into the market earlier, design cycles are reducing aggressively. To survive or grow in this challenging automotive industry, most companies are practicing cost reduction, quality improvement, waste elimination, and system engineering.

ArvinMeritor has been successfully applying lean manufacturing techniques for many years. However, lean engineering practice is still immature. ArvinMeritor's exhaust Product Development (PD) mainly includes product engineering, Computer Aided Design (CAD), Computer Aided Engineering (CAE), and various advanced testing technologies to meet the customer requirements in emission control, sound quality, legal noise, gas flow, durability target, and thermal management. The motives of this research are:

1. To integrate advanced technologies into exhaust engineering;
2. To formulate a systematic procedure to identify and eliminate waste and uncertainty.

This research is aligned with ArvinMeritor corporate strategic goals and practices.

1.2 Objective

The objective of this research is to apply lean engineering techniques to the PD process within ArvinMeritor Emission Technologies (ET) division to tackle the various uncertainties. The process uncertainty will be analyzed and defined. Improved engineering process and effective system management tools will be proposed. The objectives for this study are to:

1. Explore lean engineering techniques in the automotive industry;

2. Evaluate the lean engineering practices in the exhaust industry;
3. Illustrate the engineering value stream map of the current ET PD process;
4. Investigate the effective procedures or tools for managing the engineering uncertainties;
5. Propose an improved engineering process based on various analysis results.

1.3 Operative Approach

This research was initiated with a general market analysis of the US automotive exhaust industry. The degree of rivalry, buyer and supplier power, and threats of substitutes in the exhaust industry are briefly analyzed based on Porters' industry framework. The operational architecture of ET engineering service is then reviewed against the market challenges. The key challenges in the engineering uncertainty management are identified.

The PD process of ET is reviewed and evaluated based on lean engineering principles. A literature review of engineering process management tools follows. Several lean engineering techniques and practices are proposed to reduce the uncertainty and waste. Value Stream Mapping and Analysis (VSM/A) is used to illustrate the current information flow in the PD process. A Design Structure Matrix (DSM) is developed to analyze the current engineering process. The House of Quality (HoQ) for the exhaust system prioritizes the importance of design iterations based on their added values with respect to the customer requirements. The most critical unplanned design iterations are identified. The PD process will be simplified by tearing down several iterations which are less important. The DSM analysis suggests an improved PD process flow. A DSM simulation is performed to evaluate the improvement of the suggested PD. Further, a System Dynamic (SD) model is developed to quantify the effect of the engineering uncertainties. The complex relationship between uncertainties and the process metrics has been extensively analyzed.

Case studies are used for better understanding of the procedure and tool applications.

Chapter 2 General Review of Exhaust Industry

The current status of the exhaust industry, in terms of competition level and new technologies development, needs to be reviewed to obtain a clear vision of the emission market. In order to outperform its competitors, the strengths and weaknesses within ArvinMeritor need to be identified and analyzed.

2.1 Automotive Exhaust Market Review

The automotive exhaust market has grown in importance, and emission control is emphasized worldwide. The automotive exhaust product has become increasingly complex and more expensive with the improvement of catalytic converters, Diesel Particulate Filters (DPF), fuel cells, or Gas Turbines (GT). On the other hand, vehicle emissions regulations in Europe and US are becoming increasingly stringent. More and more vehicles will be equipped with DPFs, fuel cells, or others devices in order to conform to mandated exhaust emission levels. In response, automotive exhaust suppliers are exploring new technologies or taking advantage of the latest technologies and products to support vehicle makers to meet these challenging requirements.

In order to understand the competitive level of the exhaust business, it is necessary to analyze the exhaust industry by using Porter's industry frameworks (1), in terms of the Degree of rivalry, the Barriers to entry, the Supplier power, the Buyer power, and the Threat of substitutes.

Decades ago, the automotive exhaust system market was shared by a few firms. The competitive landscape was less competitive. ArvinMeritor and Tenneco Automotive supplied nearly 75% of North America's exhaust systems in 1999 (2). In the global exhaust market, Faurecia and Bosal are two major European exhaust suppliers, and Futaba and Sango are two dominant Japanese exhaust suppliers. In 1999 ArvinMeritor was considered the global leader with a worldwide market share of 30% (3). Before 2000, the level of rivalry among these firms was low, and the exhaust industry could be considered as disciplined. This discipline resulted from the industry's history of competition, the role of the leading firms, and the informal compliance with a generally understood code of conduct. During that low-rivalry period, any explicit collusion generally was not an option, and any competitive move was constrained informally. However, maverick firms seeking a competitive advantage over their competitors displaced the well-disciplined market. They acted in a way that elicited a counter-response by others. The rivalry then intensified, and the actions were hostile and throat cutting. To outperform their rivals, many exhaust companies went for different competitive strategies including lowering prices to gain a temporary advantage, improving product differentiation to improve product profile and to implement innovations in the process as well as in the product itself. They creatively used the distribution channels by using vertical integration and exploiting supply chain relationships to meet their demands for product specifications and price with high quality standards.

The intensity of the rivalry in exhaust industry is also influenced by the growing number of firms. According to the 2005 ArvinMeritor Business Strategy Review (4), there are more than 45 exhaust suppliers worldwide, with more than 20 new comers to the exhaust market in recent years. The important current players include Eberspacher, Delphi, Magneti Marelli, Calsonic Kansei, Futaba Industrial and Sejong Industrial. Other smaller manufacturers of exhaust system operate in domestic markets to supply emissions technologies for the niche applications. Based on an exhaust market review (5), ArvinMeritor's global market share dropped to 20% in 2004, and it has lost its leading market position to its lasting competitor, Tenneco Automotive, who claimed 25% of global exhaust business.

The large production volume required from the customer and the more advanced technologies required for higher emission control can establish an effective entrance barrier to some small operations. To breach the walls of this competitive industry, small companies have to align with the dominant companies by setting up joint ventures or technology cooperation.

The intense rivalry in the exhaust industry is further enhanced by other external factors, such as higher operational cost. Due to a lower operational margin, a company with high operational cost will eventually be pushed out of business. As an example, Delphi Automotive, the world largest automotive suppliers, filed for bankruptcy protection in 2005.

The increased competition is driving down the profitability of all exhaust suppliers. With decreasing profits, the market will be re-organized with acquisitions, mergers, or bankruptcy protection until new market equilibrium is restored. The lower profitability will deter new rivals from entering this market in the near future. Also, individual firms will keep artificially low prices as a strategy to gain a temporary advantage over their rivals. It can be anticipated that the increase of profitability will be a long-term challenge to all players in the automotive exhaust business.

From its humble beginnings the modern exhaust system has become a hotbed of expensive technologies, playing a decisive role in controlling emissions and acoustic comfort. Driven by new emission legislations, such as Euro 4 and 5, new emission control technologies have emerged in recent years, such as close-coupled DPF, NOx traps, and the Clean Exhaust Regeneration. More specifically, a number of changes have already been made on the current gasoline engines, and an increasing number of smaller cars are equipped with a manifold-coupled catalyst. These emerging technologies are substitutes to the traditional exhaust system, and the increasing pressure from those substitutes motivates and pushes the incumbent exhaust system companies to quickly possess and improve their core competency to develop a technological advantage over their competitors.

ArvinMeritor is actively involved in the US diesel exhaust after-treatment market that is growing rapidly in the process of run up to the EPA's 2007 emission regulations. The new regulations require commercial vehicles to reduce diesel exhaust particulates (mainly soot) to 0.01 g/bhp-hr. The company forecasts that the exhaust treatment technology market will soon be worth US $1.6 B a year and it has developed a range of products and processes to address three specific problems: to develop Thermal Regenerators (TR) or DPF to reduce the Particulate Matter (PM), to launch Selective Catalytic Reduction (SCR) to reduce the NOx emission, and to invest in Diesel Oxidation Catalyst (DOC) to enhance hydrocarbon emission control. The company has developed a portfolio of products for gasoline engine vehicles. As one of the leading manufacturers of DPFs, ArvinMeritor currently supplies more than ten OEMs. The confirmed new orders are driving a strong increase in production, with 2007 annual production estimated to exceed 1 million units for the first time, and the company will supply nearly 1.2 million DPFs by 2008.

In addition to being challenged by new technologies, exhaust system companies are also getting more and more pressure from their suppliers. The exhaust industry is one of the largest consumers of stainless steel for pipes and mufflers, and precious metals for converters. Stainless steel is a typical commodity, and its price will fluctuate based on the market requirements, which leaves little or no control for the consumers. Again, the higher steel import tariff increases the cost pressure to industrial consumers and reduces the possibility of importing the stainless steel from other countries. The increasing raw material cost will further enhance the strong supplier power, and put the exhaust industry into an even worse position.

While new emission norms spell out good news for exhaust manufacturers, there are signs that they are being over stretched. Clearly, emission norms will increase the average wholesale value of the exhaust system and its constituent parts; however, this will be partially offset by the continued pressure on suppliers for annual cost reduction. The value chain of the US automotive industry is composed of OEMs and their tier suppliers at different levels. The OEMs, as buyers to their fellow tier suppliers, have absolute control in this hierarchical system. The buyer power for the exhaust industry is extremely strong and the exhaust companies have less bargaining power in the whole value chain. Actually, the exhaust and emission system is only about 3% of the total vehicle value, which is negligible and partially contributes to the unbalanced relationship between automotive OEMs and exhaust suppliers (6). The US automotive market is traditionally shared by GM, Ford, and DaimlerChrysler, even though their global market share is losing out to foreign automotive companies such as Toyota, Honda, Hyundai and other foreign automotive OEMs. Compared with the aftermarket sales, the sales to OEMs dominate the businesses of US exhaust suppliers. The US automotive OEMs are highly concentrated and possess an incredible backward integration threat to the exhaust suppliers. All these observations indicate that the buyers, automotive OEMs, are extremely powerful. This hierarchical system will not disappear in the near future.

The industry analysis of the automotive exhaust market shows the opportunities and challenges in the automotive exhaust market. The competition in the exhaust industry is intense, and both the supplier power and buyer power are strong. Potential substitutes are emerging and threats from substitutes are approaching. In realizing those unfavorable situations and threats, the exhaust manufacturers are improving their business and engineering, including the removal of waste and uncertainty. The ideal engineering process should be lean, efficient, and perfect.

The ET at ArvinMeritor used to lead the exhaust market in terms of technologies and the market share. However, ET's market share is reducing. In order to regain the competences, ET has a long way to go. To better understand the ET division of the company, it is necessary to review the challenges and opportunities within the division.

2.2 Challenges to ArvinMeritor Emission Technologies

The previous market review shows the difficulties for ET to survive and grow in this highly competitive industry. The ET division of the company is being challenged by multiple factors:

- To keep a lower price in order to win new business from customers while paying higher prices to buy raw material from market
- To delivery higher quality product to meet various OEM requirements within limited resources

- To support its R&D develop technologies to outperform its competitors or to relieve the threats from the substitutes

The major buyers, automotive OEMs, can put ET into a passive, reactive or firefighting position. ET always plays catching-up right before or during a production launch. Even though ET is identified as a high-tech engineering company, it has to focus more on the manufacturing, and leaves engineering as the supporting role to the manufacturing. Advanced technology is not leading the manufacturing; instead, it is struggling with late engineering changes or failures. This sticky situation will eventually erode the limited core competencies within ET division.

Great efforts have been made to optimize the performance of the company in the last several years, such as ArvinMeritor Performance System (AMPS) including Design Excellence, Business Excellence, Production Excellence, White Shirt People Excellence, and Supplier Excellence. The objective is to reduce engineering waste and enhance the core competencies to lead the technologies and the exhaust business. Prahalad and Hamel (7) define the term - core competencies as the collective learning and coordination skills behind a firm's product lines. They are the sources of competitive advantage. The core competencies must be able to:

1. Provide access to a wide variety of markets;
2. Contribute significantly to the end-product benefits;
3. Be difficult for competitors to imitate.

However, the AMPS is still at its initial stage. Its effect on the overall performance of the company is quite limited. In 2004 financial year, the operational margin within the ET division dropped 0.5%, despite the annual revenue increase of 6% (8). The drop is partially due to the higher cost in materials and engineering. Since ET cannot control the steel price, it has to focus on the reduction of engineering cost. The intention to reduce cost and to improve efficiency does not mean to simply reduce the number of various entities. It should be to more effectively examine the functional requirements and scale them against the functional dependencies. To address this, the framework showed in Figure 2.1 by McCue (9) is applied.

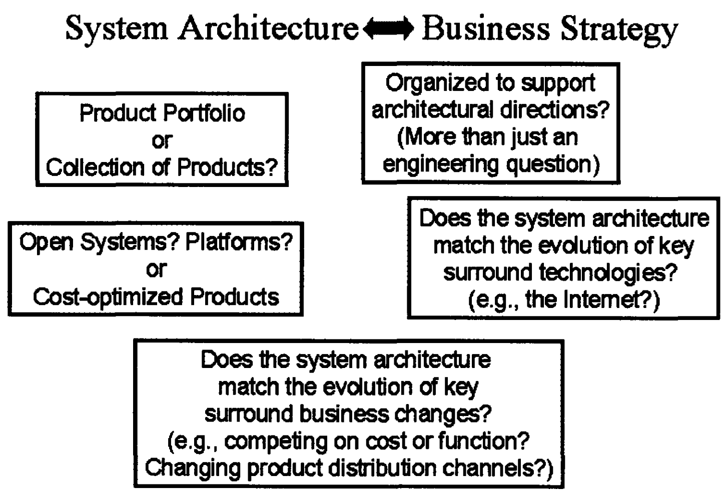


Figure 2.1 McCue Architecture of Business Strategy

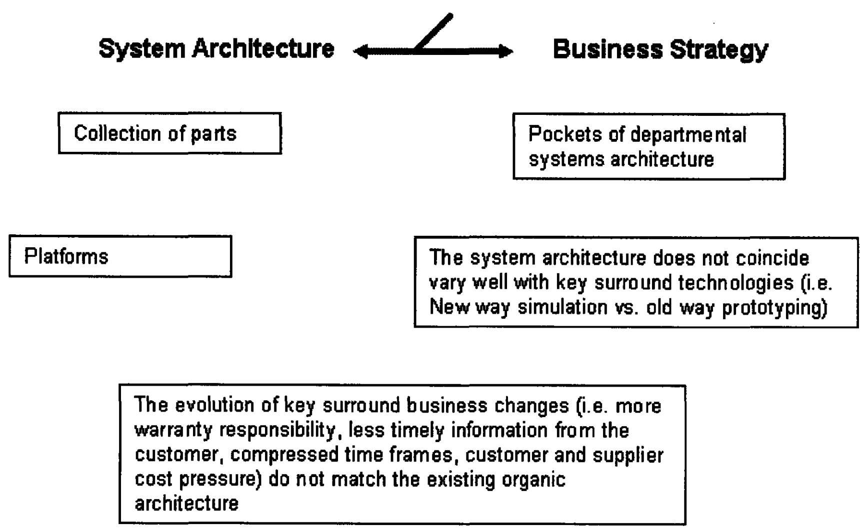


Figure 2.2 ET Architecture for Business Strategy

Figure 2.2 is the reflection of current ET's engineering with McCue's framework. The key challenges for the engineering service in the ET division are summarized as follows:

1. More warranty responsibility;

2. Less timely information from customer;
3. Compressed time frames for engineering changes;
4. Customer and supplier cost pressure;
5. More advanced predictions versus old way prototyping.

These factors will largely generate uncertainties or dynamics in the engineering process, which increases the engineering cost. Because of the uncertainties, even the routine engineering services for the existing business are always in deep difficulty. No sufficient knowledge, tools, resources, cooperations and coordinations are available to quickly iterate multiple designs. It is always difficult to effectively and quickly find the solutions for the failure or noise problems. Well-planned and validated systematic approaches are required to economically select the most feasible and most cost-effective design or option. This is because more efforts within ET are consumed in the re-works, and the investment in the new technologies and applications has been limited. Hazelrigg (10) discusses the nature of engineering design: engineering design is not merely decision making, it is decision making under uncertainty and risk. To increase the efficiency of ET's engineering, the effective handling of uncertainties in engineering is a key factor for engineering cost reduction. The cost is not only limited to financial cost, but also refers to the cost of manpower. A process with lower uncertainty will improve the process efficiency and increase the profit margin. With the efficiency improvement, ET will have more resources to invest to its core competencies, and keep itself in a better competitive position.

Core competencies do not simply result from hiring a team of brilliant scientists in a particular technology. Instead, core competencies should be embedded in the OEM Architecture. Figure 2.3 shows an OEM Architecture suggested by McKinsey's 7-S model, in which the core competency is a part of "Skill". McKinsey's framework shows that there are seven closely linked units inside a company. Improvement of the competency or "Skill" requires cooperation among all seven units. The best practice of all seven units must be achieved in order to improve the company's overall performance. The "Skill" and the "Staff" are two basic elements, which compose the engineering process. An optimized engineering process will be a determinant factor for the successful operation of a company.

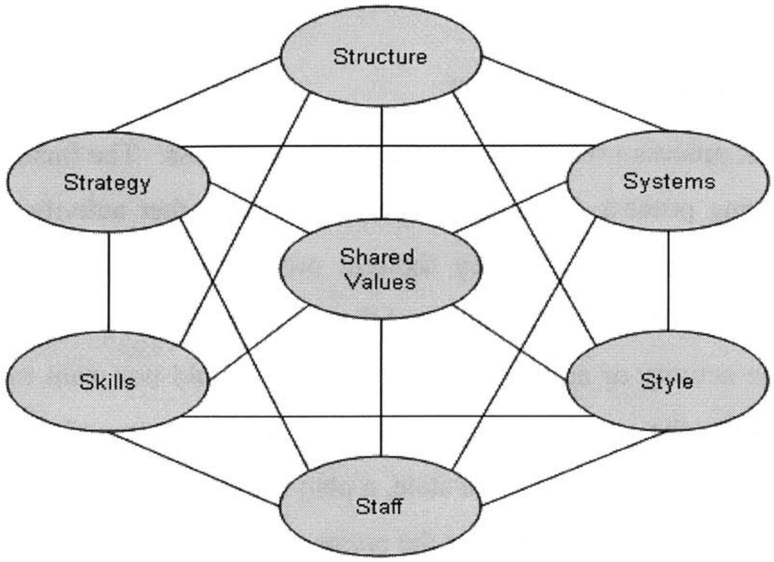


Figure 2.3 McKinsey 7S Model

To achieve cost reduction and enhance core competencies, the “Skill” must be constructed to consolidate the abilities to generate core competencies with all resources. The increased core competencies will increase the company value in the whole value chain. Eventually, it will turn the ET division from a passive position into an active position.

Chapter 3 Literature Review for Lean Engineering Practices

3.1 Concept of Lean Thinking

Lean is a thought process used to review the business process. The business process can be a manufacturing process, a service procedure, or any other activity where suppliers and customers are involved. The key thought process within lean is to identify the 'wastes' from the customer's perspective and then determining how to eliminate it. Waste is defined as the activity or activities that a customer would not want to pay for and/or that add no value to the product or service value from the customer's perspective. Once waste has been identified in the current state, a plan is formulated to reach the future state in an effective manner that encompasses the entire system.

Lean principles can be applied to any kind of business and to all levels within the business. The highest level is the lean enterprise, which includes lean leadership, lean engineering, lean manufacturing, lean supply chain, and lean organization. Figure 3.1 (11) summarizes the family of lean enterprise. Each specific lean strategy has its own main objectives. Various tools are available to be shared by different lean practices. Automotive OEMs and suppliers are all moving towards the lean enterprise, with different focuses on leadership, engineering, manufacturing, supply chain, or organization. Different progress or achievements have been made within different companies and different area. The lean practices are to identify and specify the customer values, to define and map the value stream, to identify and remove the wastes, and to smooth and focus on continuous flow as pulled by customers. Lean engineering should be a lifetime activity if the company wants to survive and continue to grow.

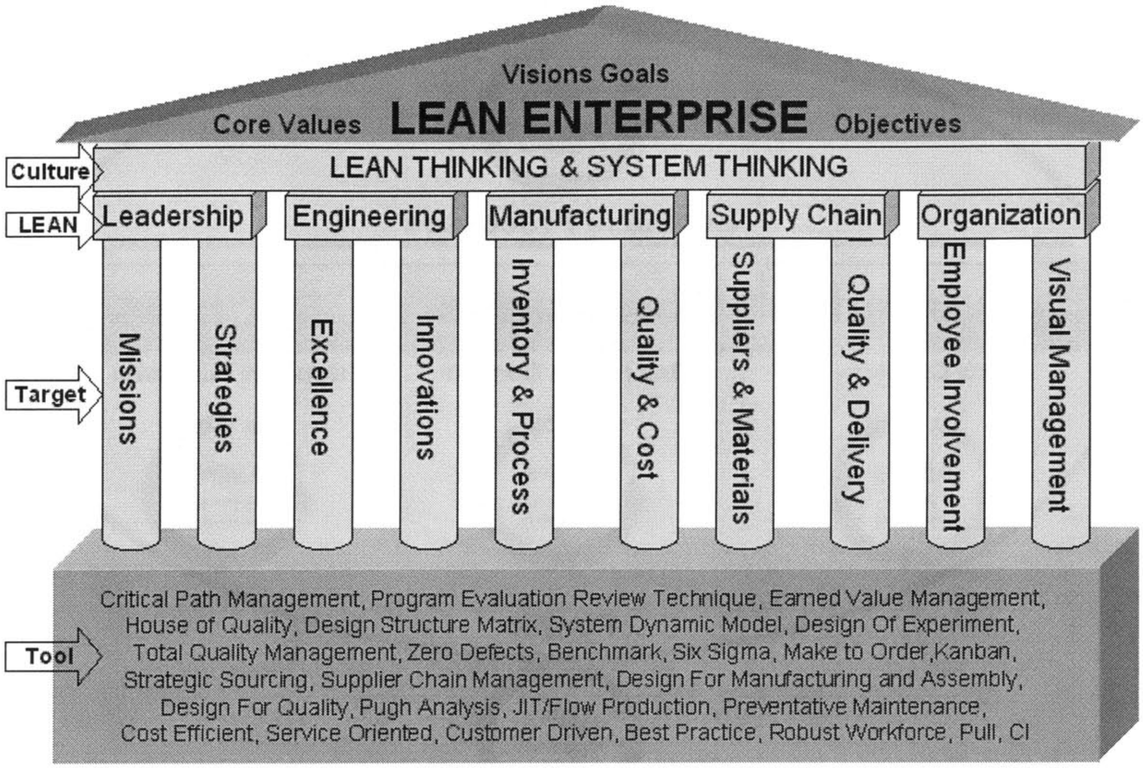


Figure 3.1 House of Lean Enterprise

Lean approaches have been practiced in ArvinMeritor for several years. The AMPS program at ArvinMeritor Light Vehicle System (LVS), shown in Figure 3.2 (12), has five core excellences (or leans) including Business Excellence, Design Excellence, Production Excellence, Supplier Excellence, and People Excellence. The excellence programs can be well correlated to the Lean Leadership, Lean Engineering, Lean Manufacturing, Lean Supply chain, and Lean Organization, correspondingly. In this research, the key focus is on Design Excellence or Lean engineering. The current activities or practices within ET engineering will be first reviewed against the lean criteria for the exhaust engineering.

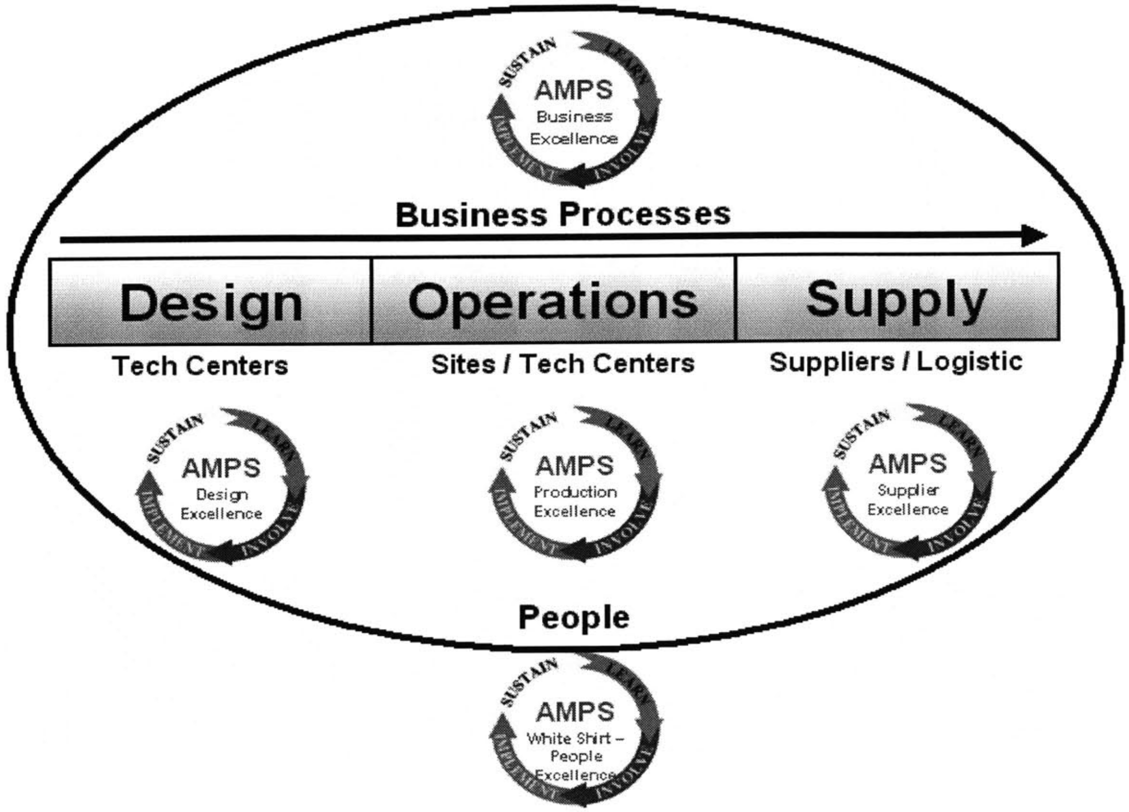


Figure 3.2 Lean Practices at ArvinMeritor

The influence of the ArvinMeritor lean application on the exhaust manufacturing process has been strong, but the lean improvements in manufacturing alone can have only an island effect in the final exhaust system product value. The entire division or enterprise must undergo a lean transformation for the impact to be significant, and the key is the lean engineering. Although exhaust engineering's contribution to the exhaust system lifecycle costs is modest, both the eventual lifecycle cost and user satisfaction are determined by the engineering. Fabrycky (13) estimated that about 80% of the product's lifecycle cost is determined before the stage of detailed design. This percentage for exhaust business is around 50% to 60%. Therefore, to make the exhaust system products valuable, effective engineering is most important.

Figure 3.3 shows the relative cost of any design change at various stages in the product lifecycle process (14). The cost to fix the problem in the final production stage will be 10,000 times the cost to fix the problem in the initial design stage. It will be also much easier to get things right earlier than to fix the engineering mistakes later. On the other hand, the users' satisfaction with the value produced by the product is also largely determined by the design of the product. The production and service of a quality product will not be valuable if the product itself does not please the customer.

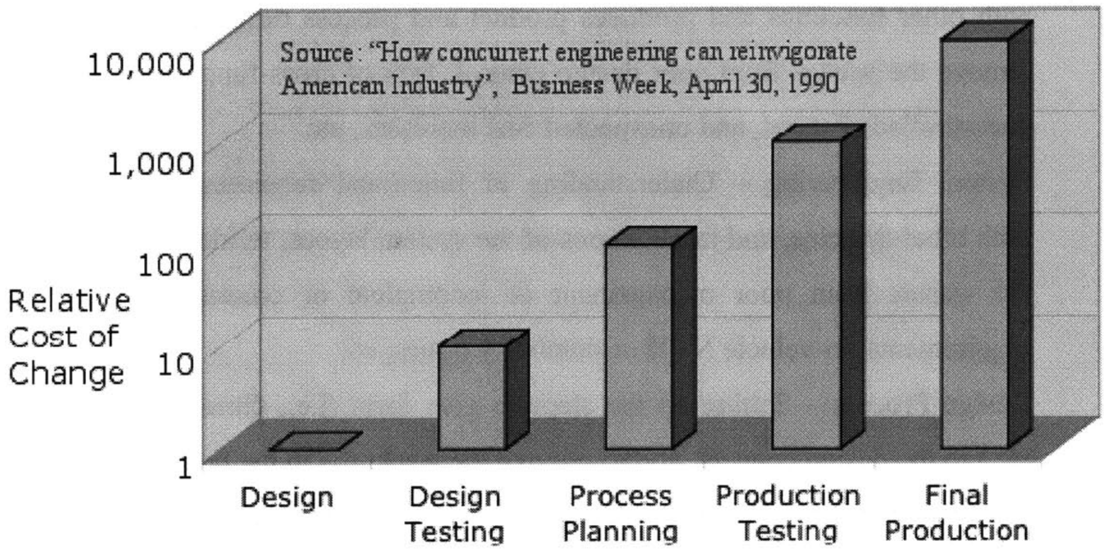


Figure 3.3 Relative Costs of a Design Change

The application of lean techniques to automotive PD processes is underway across the automotive industry worldwide, although the techniques for lean engineering are not well established yet, and many practitioners or companies are learning the experience. In general, lean engineering has three goals, representing three very different areas of process improvement:

1. Creating the right products – Creating the product architectures, families, and designs that increase value for all enterprise stakeholders;
2. With effective lifecycle and enterprise integration – Using lean engineering to create value throughout the product lifecycle and the enterprise;
3. Using efficient engineering processes – Applying lean thinking to eliminate waste caused by uncertainties and to improve cycle time and quality in engineering.

As presented in Figure 3.2, the ArvinMeritor Design Excellence program is designed to address similar issues or goals for lean engineering. In its design excellence program, four dimensions are addressed:

1. Engineering Systems – Understanding how an engineering group works, interacts with other functions and produces product and process designs, to identify and remove the wastes from poor design control, lack of cross-functional discussion, uncontrolled changes, and unexpected cost increases, etc.
2. System Engineering – Understanding of functional requirements, interactions with other systems, and implications of the system layout, to identify and remove the wastes from poor management of incomplete or contradictory customer requirements, in-vehicle NVH or durability issues, etc.
3. Design Process – Setting up the steps to give form (i.e., dimensions, materials, etc.) to the design concept, and to remove the weakness in the design process. The weakness includes that the product functionality is sensitive to process variations and that the tolerance stack up not in 3σ;
4. Product Space – Extending the complete lifecycle of the product from innovation to disposal, to avoid warranty issues due to poor design.

To effectively perform a lean study of ET engineering, the three generic lean engineering goals will be used as the baseline and the design excellence program will be the main reference for the integration of exhaust engineering service. Different lean approaches, tools and best practices will be described, evaluated and used in this study.

3.2 Creating the Right Products

The objective to create the right products is to create the right product architecture, families, and designs that can increase values for all enterprise stakeholders. During the fuzzy front end of exhaust system development, the beginning of concept development, the engineers will encounter many uncertainties: 1) evolving customer requirements; 2) various users' preferences; 3) imprecise specifications of product parameters; 4) confusing product functional objectives and packaging objectives; and 5) varying levels of technology maturity in emission, thermal, vibration and durability. To embark on lean practice in this early stage, many best practices and approaches can be involved.

The first priority is to focus on the understanding of customer and end user value expectations for the product, such as features, attributes, quality, price, cost and availability. The most difficult processes include the value definition and creation of the less-than-fully-defined users' values at the beginning of PD, and the prioritization of multiple customer requirements or design objectives. In automotive exhaust system development, the functional objectives are:

1. Lower backpressure to maintain engine power and fuel consumption efficiency;
2. Lower emissions levels to meet the more stringent government regulations;
3. Better sound quality to satisfy the driver and riders, and the lower legal noise level to pass the environment control;
4. Longer durability target to extend the product lifecycle;
5. Better thermal management to better control the temperature, thermal expansion and thermal radiation.

The packaging objectives for the exhaust system are:

1. Appropriate catalyst volume for the emission control;
2. Appropriate muffler volume to tune the noise;
3. Best and feasible hanger locations to reduce vibration;
4. Well-balanced centerline routing to accommodate other components.

It is necessary to study how the aspects of various customer objectives can be systematically evaluated, how various engineering groups can work together, and how the interactions of multiple functions to be handled. Slack (15) suggests a customer value framework, Figure 3.4. The framework shows that the customer value should be achieved with the involvement of multiple functional teams, such as product quality, functionality, schedule, and price. He also suggests that the informed negotiation of goals for PD would maximize value for as many stakeholders as possible.

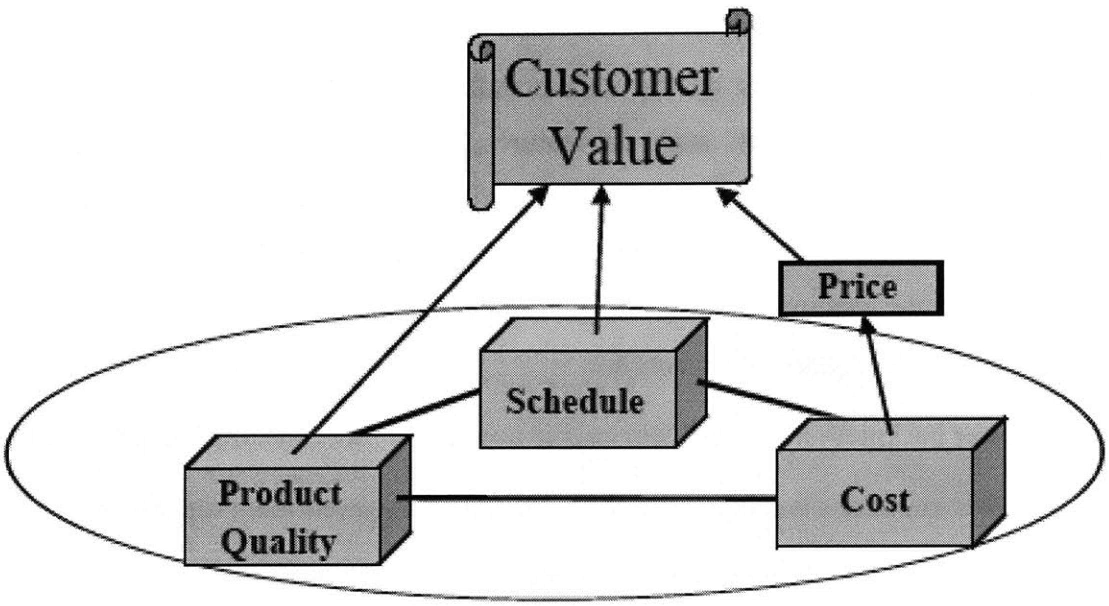


Figure 3.4 Slack's Customer Value Framework

An opened "design space" is required to address uncertainties in the concept development stage before sound decisions are made. Toyota's set-based design technique is a good example, in which it intentionally delays the final decision even into the detailed design stage until the most reliable information is ready. However, Bernstein (16) found little good evidence of set-based thinking in aerospace, noting an opposite trend of making early decision on product architectures and features. Some options, approaches, and other uncertainty management strategies are under study and will be available to address this challenge in terms of lean engineering.

The design and engineering standardization will greatly increase the capability in handling the uncertainties. The architecture of products should be developed with the capability to be upgraded or improved in future product offerings. In automotive exhaust system development, the standardization improves the re-usability of products, such as tuning code of muffler and resonator, standard straight and bent tubes, and other design standards. These are all good lean engineering approaches to reduce uncertainty-induced cost and development time for new products, while still improving the product features, attributes, and quality. The traditional "point designs" that are highly optimized and specialized solutions to specific problems are not considered as good practices for lean engineering. Highly specialized technology may bring high return, but it should not be treated as a dominating factor in PD for the purpose of lean engineering due to its higher risk. The engineering uncertainties can be largely reduced or removed by using proper approaches. The DSM method together with the HoQ technique could be used as an effective approach to review, evaluate and analyze the system project process from the beginning to the end.

A general framework to effectively analyze a "fuzzy front end" PD process was developed by Wirthlin & Rebentisch (17), and Wirthlin (18). It can be used to determine how successful organizations make decisions from many product perspectives. In the exhaust industry, the products can be quite different in terms of customers, platform and configurations. The following framework and best practices are suggested and developed specifically for the automotive exhaust systems:

1. Requirements identification:
    a. Forming a best-in-class project quotation team with multi-disciplinary backgrounds including program manager, product engineer, specialists in emission, thermal, durability, and NVH control.
    b. Evaluating the new PD process strategically, such as Quality Function Deployment (QFD) approach, which is effective in long-term strategy analysis, but not for quick-fix solutions and existing products or technology.
    c. Architecting the product architecture to understand the customer requirements and needs with proper tools, such as Objective Process Methodology (OPM).
    d. Determining the interrelationship among customer attributes, requirements, objectives, cost, and technical uncertainties clearly, with certain system engineering techniques, such as the "HoQ". (19)

e. Generating product concepts with multiple iterations, by using certain concept generation tools, such as Pugh's concept generation process (20).

2. Initial Screening

a. Selecting proper project to quote by a senior program team.

b. Managing portfolios actively, such as the Concept-to-Customer (C_2C) program at ET of ArvinMeritor.

c. Prioritizing projects based on the company strategic plan, doctrine, or product strategy and resource constraints.

d. Adopting the standard process for the concept selection. Ulrich and. Eppinger (21) suggested a concept matrix to screen, score, and select--identifying all uncertainties and schedule action plans with project management tools, such as Critical Path Method (CPM), Project Evaluation Review Techniques (PERT), and DSM, etc.

3. Concept Development

a. Converting requirements or objectives to the measurable variables within a desired range; identifying the technique challenges in concept stage, such as lower engine backpressure verses higher tuning requirements.

b. Preserving organizational memory during whole process with the development team remaining intact. The PD cycle usually lasts 3 or 4 years in exhaust industry. It is important to keep the experience within a specific product during the whole development period.

c. Simulating alternative concepts with data generated through prototypes, always having a backup design ready in case of customer requirement changes.

4. Case Development

a. Synthesizing concept, architecture, and concept of employment

b. Fitting the concept with organizational portfolio based on product, technology evolution/insertion, and product replacement strategies.

To be successful at the front end, both leadership enablers and infrastructure enablers are required. Leadership enablers include the management roles and responsibilities, team integration, and skill development and training; Infrastructure enablers include R&D, IT support, and other resources. The best practices to create the right products should be continued into system-level and detailed design. Dare, et al. (22) suggest that the effective use of a "system representation" such as a computer model, a prototype, or a modified existing system would greatly facilitate communication and design adaptation. The needs of customers and end users could be better delivered. Customer and supplier involvement throughout the design process, being the member of Integrated Product Teams (IPT), Virtual Reality Reviews (VRR), and other lean engineering processes, will contribute to capturing the detailed needs and creating the right products.

3.3 Effective Product Lifecycle and Enterprise Integration

McManus (14) suggested a product value chain, shown in Figure 3.5. It depicts the role of key stakeholders in delivering the expected value. The value stream chain is a set of stakeholders that are linked together to form the value flow stream during the product design and development process. The customers specify the values and requirements. The company sets up the objectives to meet the requirements with sufficient features, justified cost, and prices. It is the responsibility of the engineering department to design the products that are producible with excellent performance and high quality, and can be delivered on time. It will be necessary for all stakeholders – customers, engineering, manufacturing, suppliers and partners – to work closely. Bozdogan et al. (23) estimate that 60-80% of the product (by value) is outsourced. So the involvement of all the suppliers early in the PD process is extremely important. Suppliers or partners may have considerable knowledge and experience to add value to the product. The information should be openly and seamlessly shared between the OEM and their suppliers. The OEM should even invest resources to help partners and suppliers become lean, which will be mutually beneficial.

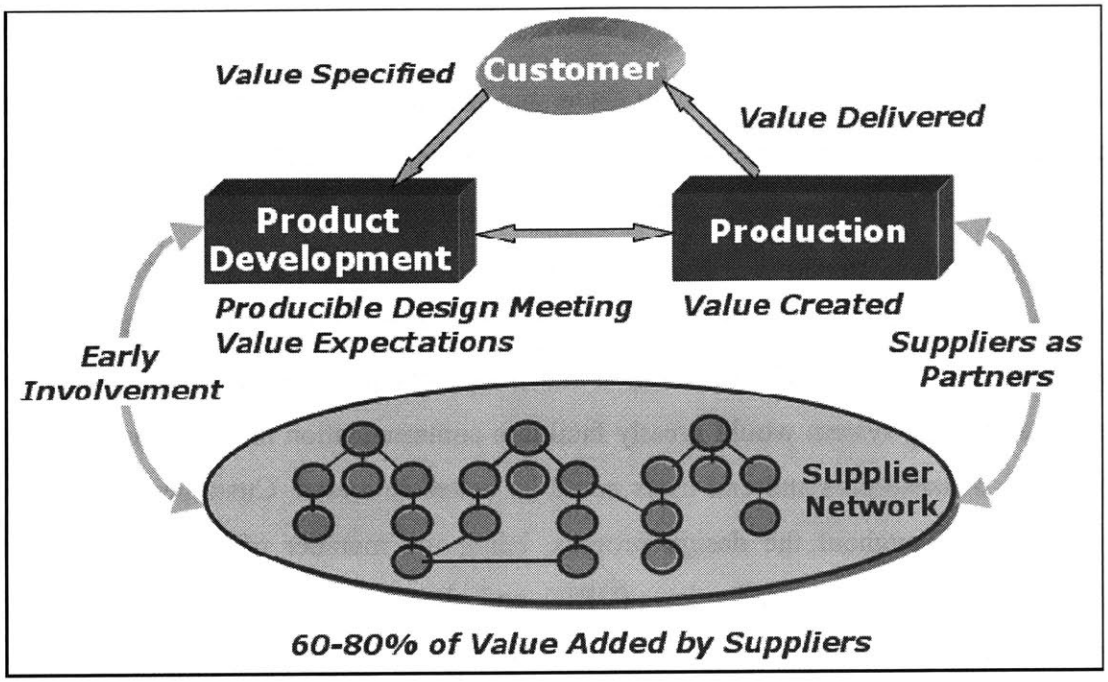


Figure 3.5 Product Value Stream

The system engineering approach is needed in order to develop the top-level architectures of the product. Based on the systematic engineering of the PD, the mandatory or latent customer requirements can be flow-down to detailed specifications or objectives that will be carried through all development cycles, which includes the concept design, the system level design, the detailed design, and the final design stages. With respect to automotive exhaust system design, the end users' requirements can be categorized as follows:

1. Packaging requirements - Catalyst volume, tuning volume, hanger locations, and centerline routing;
2. Functional targets requirements - Backpressure, flow rate, emissions, sound quality, legal noise, durability target, and thermal management;
3. Life cycle requirements - Reliability, maintainability, and supportability;
4. Economical requirements - Unit cost and lifecycle cost.

To successfully carry out the system engineering is the fundamental requirement to integrate lean engineering into the exhaust system value stream. To achieve the competitive competence in the exhaust market, the engineering department should invest sufficiently to embark on and continue with the innovation and advanced R&D. To develop a competitive edge over its competitors, the company must continue implementing current available advanced technologies into current PD, and following the lean principles to eliminate waste from current engineering processes.

3.4 Lean Practices in Automotive Exhaust Industry

To implement lean in engineering service, the routine engineering activities including design, simulation, and testing, should be well managed, smartly coached, and efficiently integrated to shorten the PD cycle time, to improve product quality, to identify and eliminate all wastes, to reduce the product lifecycle cost, and to sufficiently meet the customer requirement. Following are some available methodologies and procedures for the lean practices in exhaust industry.

1) R&D - Research & Innovation

   Firefighting is a common phenomenon in automotive tier suppliers that has consumed a large amount of financial and technical resources. As an exhaust supplier, ET always falls into a dilemma in distributing its work loads between services for existing business and the R&D activities. In the automotive industry, the tier suppliers are extremely customer oriented. The automotive OEM exerts various constraints on their suppliers at different design stages including concept generation, system design, detail design, and final design. Most of time, the exhaust companies are inactive or passive in dealing with customers' sudden or late changes. These catching up or firefighting activities could take in almost all the resources the suppliers can have. Furthermore, deficient investment in their R&D will eventually put the companies into the risk of being disrupted by new technologies. Eventually, the companies without sufficient competencies will be driven out of market, as discussed by Christinsen (24). A sophisticated and successful company should always pay enough attention to disruptive technologies to keep the company surviving in the market. The requirements of current customers will be reasonably met and satisfied within the company boundaries or limitations.

For the automotive exhaust industry, the more stringent emission control regulation is a challenge to all exhaust suppliers. Tremendous efforts have been made by suppliers as well as OEMs to develop new technologies to reduce the pollutant content in the vehicle emission, such as using precious metals in the catalyst substrate to improve the effect of oxidization, or increasing the cell density of substrates to increase the performance efficiency. Successes in effective emission control have been achieved at certain levels; however, these achievements are still customer oriented. The tier suppliers' R&D efforts have been highly focused on customer satisfaction, and the supplier roles are still reactive or passive.

The embryo of automotive emission related disruptive technologies has emerged already. Fuel Cell technology, for example, is a potential technology to disrupt the traditional engine technology. Although the fuel cell is still expensive and has the supporting infrastructure problem yet to be solved, it will push the exhaust suppliers out of business easily when the technology is mature and economic enough to be installed on vehicles in the near future. To keep or improve the core values of companies, exhaust companies should continue investing in their core competency through R&D activities. The R&D should not be only focused on the current customer requirements with traditional technologies, but also on the end users with the potential disruptive technologies.

2) DFM - Design For Manufacturing:

DFM is an integrated component of the design process that bridges the gap between design and manufacturing considerations, ultimately affecting cost, performance, and manufacturability of exhaust systems. The variations and tolerances in manufacturing various parts and components should be well defined, monitored and recorded. The design of any specific product should always be based on the tooling, procedure, and available resources in the manufacturing plant. The re-design due to unpractical product specifications will require additional engineering activity, which is a big "muda" and needs to be removed immediately. The integrated design of the product should accumulate the learning from the experience, and accommodate most available tooling and equipment information. Thus, it can largely reduce the uncertainty and its associated costs in the manufacturing and engineering process. This is extremely important for automotive exhaust suppliers, who are operating at lower profit margins and rely heavily on the DFM to reduce the production cost.

3. DFQ - Design For Quality:

Product quality always has the highest priority of a business. The exhaust system should first meet all required functional requirements for emission, NVH and durability. The durability concern and the structural-born noise will always be the focus for quality concerns even after production. A successful system design of an exhaust product should improve the new designs with the learning from CAE, testing and experience. General rules have to be set to instruct the designer to make decisions for hanger design, such as a brace to reduce the durability concern; the best hanger locations to attach hangers; the optimized baffle space to avoid radiation noise from the muffler shell; and the appropriate length of throat to remove the resonance and durability concerns with a muffler. The repeated mistakes on these local designs are the biggest wastes within an organization, and should be removed with proper standardization and procedures.

4. CAD – Computer Aided Design

The integrated computer-aided design tool utilizes the parametric solid models technique to quickly transfer the concept into a visual prototype. Most exhaust companies are taking advantage of various CAD software. The selection of software, the compatibility of CAD results, and the management of various designs are normally the major concerns. The standardization of certain parts and components is a long-term process, and some design standards need to be updated or improved with experience from the test and CAE results. Design engineers should also conduct simple analysis so as to avoid some mistakes and re-works. The whole design cycle can thus be speeded up. The systematic training of the CAD experts is the key to keeping the CAD activity lean and effective. The efficient CAD will solve or remove most of the internal uncertainties in the "fuzzy front end" stage.

5. CAE – Computer Aided Engineering

CAE gives a systematic evaluation of a set of designs, by applying the virtual load and boundary conditions to the finite element model to simulate dynamic responses and predict the fatigue lives of parts, components or systems. It could greatly reduce the iteration time of the development cycle and the number of prototypes. To keep a sufficient amount of software and tools is recommended, and the training and keeping of the CAE experts are all necessary. The expertise includes the emission simulation, NVH simulation, thermal simulation and structural vibration simulation, etc. The leading research projects should include the advanced methodologies, comprehensive correlation with tests, new technologies development, and other special programming. The standardizations and specifications about modeling, assumptions, procedures, and result interpretation should be the first tasks for the successful CAE services. The CAE is expected to play a major role in reducing the automotive exhaust system development cycle.

6. Advanced Test Technologies

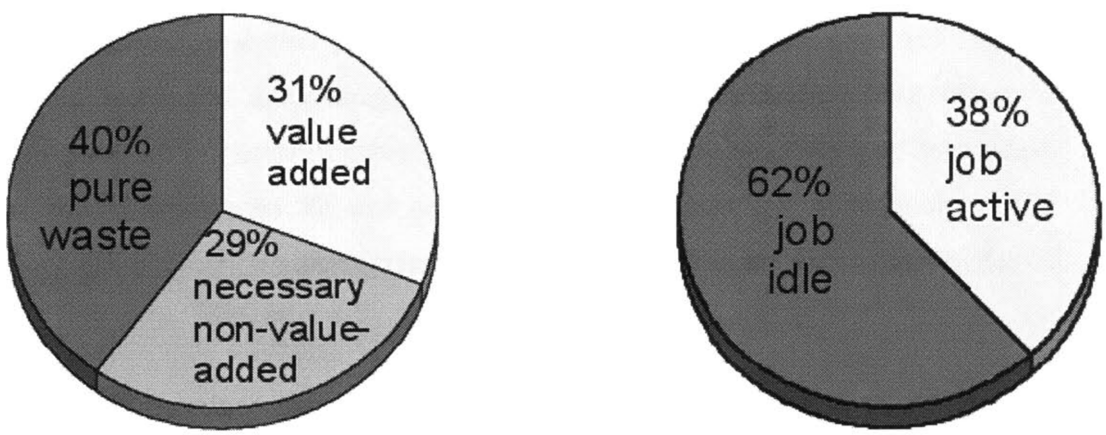
To quickly verify the design or product, various physical tests play key roles in the PD process. Even though normally expensive and time consuming, and in need of a prototype, the advanced test technologies will provide more convincing results than the simulations. The good planning of various tests, the effective processing and extensive usage of the test data will be big challenges to the exhaust companies. With automotive engineering relying more on the CAE, the physical test will play a key role in providing load inputs to CAE models and correlating and validating of the CAE models and results.

7. Database Management and Standardization:

The standardization process is the key to removing any waste caused by the process uncertainties. Standardization can be applied to the whole PD cycle including the CAD, CAE, Test and manufacturing. Various models and data should be able to be shared and be compatible with that from other functional groups. The upstream information should be accurate, complete, available and accessible to downstream users within the same organization. In general, all the data should be well maintained and kept as the proprietary values of the company. Miscommunication and waiting for information can all be removed with an effective standardization and database management system.

Different processes or different industries may need different lean engineering tools to identify and remove the waste from the process. Many companies have a vague map of their engineering process. Some processes are poorly defined and kept, such as the obsolete practices, irrelevant details, and lack of key practices. The companies may still capture the once critical important practices, but they have become obsolete over time. These are considered as the monuments from the view of lean (25). The quality work, if there is any, has been accomplished only with the professionalism of engineers and managers who are involved in the conservative review and the verification practices.

The overall engineering has high potential for process inefficiency. Survey (26) results, shown in Figure 3.6a, are based on the engineer-charged hours for the aerospace industry. Engineering inefficiency is a serious problem: about 40% of an engineer's effort is described as pure waste, and only 30% is value added. Joglekar's study (27) confirms that about 35% of engineering effort is typically wasted. Figure 3.6 b shows the even worse data, which is collected on work packages from a lean point of view. When engineering work packages are tracked (as opposed to engineers), the inactive time is about 60% of total work (28). Since these idle or lower productivities may not induce much cost, the company will not be in a hurry to change them. However, if the company is under pressure to reduce its engineering costs or to improve its performance efficiency, these inactivities and idles are not bearable anymore. The PD cycle time will be easily doubled simply due to the wastes. Every company should actively seek methods to reduce or remove these wastes in their engineering process.



a) Value Assessment of Hours b) Activity on Work Package

Figure 3.6 Engineering Time Allocation

Combining above data together, an alarming picture will show that a typical work package only have about 12% of the time with value-adding activities, and the 88% of the time is in a state of pure waste, either idle or undergoing useless processing. This alarming picture is confirmed by multiple independent sources: LAI *Kaizen* process improvement events reveal 75% - 90% job idle time in the bottleneck processes selected for improvement (29); an LAI simulation (30) has regenerated similar results. The cumulative picture resulting from these sources shows that 60% - 90% time is wasted in a typical engineering process, even if all the steps are still value added. The waste will still exist even if all involved engineers are busy all the time and only 60% of their time is valued added or busy with enabling activities.

3.5 Lean Implementation in Product Development Process

The fundamental difference between the engineering process and the manufacturing process is the uncertainty. The input to the engineering process is information rather than physical material, and the output from the engineering process is the product specification rather than the product itself. Both are "soft" products, which can be easily changed. Normally, the PD process is a combination of various jobs. It has greater difficulties and complications, which make the application of process improvement extremely complicated and difficult.

In general, the uncertainties in the whole PD cycle, including design, analysis, test, and manufacturing, have negative impacts on product quality. Thus various lean techniques for uncertainty control, such as Engineering Risk and Benefit Analysis, Set-based design etc., should be used to guide all activities in the exhaust system engineering. The following are the most common methods in engineering design: set up the proper tolerance, provide multiple selections, perform risk evaluation, and prioritize targets. The purposes of these methods are to assure the good first-time assembly fit, to maximize benefit, and to reduce the overlap and re-work. Therefore, the re-work caused by the uncertainties can be minimized.

The basic concepts of Lean Thinking - value, value stream, flow, pull, and perfection - can be reflected in the engineering process. The values, especially for an on-going process, are harder to recognize. And the definition of value-added activities is even more complex. The flow of a value stream is composed with information, technology, experience, and knowledge. They are all untouchable and cannot be tracked as easily as material flow in a plant. Sometimes, engineering iterations can reduce the uncertainties, which is rarely true in manufacturing. The "pull" to which the engineering process should respond is not only the customer requirement. Indeed, the engineering process should also be ready to tackle the process uncertainties. A mature engineering process should be able to minimize the uncertainty induced cost.

In terms of overall engineering value stream, the PD processes are only several intermediate or interdependent steps within the whole enterprise value stream. The engineering value stream is designed to create value, to deliver customer need, to improve quality, and to reduce the engineering cost. The perfection in engineering needs to be re-defined to match the enterprise value stream. The efficiency in a PD process is only an enabler of better enterprise performance. The final goal of perfect engineering is not only to complete development fast and perfectly with minimum resource, but also to be able to maximize its value generation capacity to the entire enterprise value stream. To achieve this, lean engineering practice is required. To apply the lean practices in PD processes, various lean techniques in process management can be selected. The main objectives are to make the PD process be efficient, reduce engineering costs, shorten the engineering cycle time, and well allocate resources. With sufficient investment in the R&D related innovation and best practices, the company will be able to select the right product and design the product in the right way.

Since the initiation of lean practice at Toyota a half century ago, effectiveness in project management has always been listed as the top priority in strategic management. Among various tools, the system project management is one of the most important approaches. The system project management requires a clear map and analysis of the engineering value flow, and the importance of various process steps needs to be prioritized.

The fundamental basis of lean engineering is to identify the value stream of an enterprise. All activities inside the enterprise should follow the value stream closely and the entire value stream should flow smoothly. Hugh (31) defines the Value Stream Analysis (VSA) as a method by which managers and engineers seek to increase the understanding of their company's development effort in improving the engineering. The main goals of VSA are to explore the development process, which can add value to the product, and to efficiently link the values together into a continuous and smooth flow of the value stream. VSM is a tool to support VSA, and it is the method by which the outcomes of VSA are depicted or illustrated. Figure 3.7 is an example of a generic VSA for an exhaust PD process. The value of the PD process can be defined as the capability to deliver right product at the right time, for the right price, and with the right function defined by the end users.

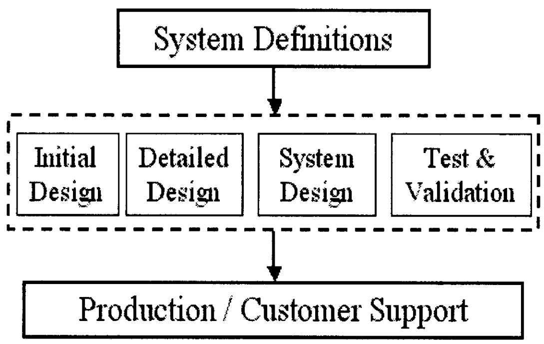


Figure 3.7 Generic VSA for PD

After the value stream is mapped and analyzed, various project management tools can be applied to individual projects to achieve process efficiency. In 1957, DuPont developed the CPM, which is designed for projects that are made up of a number of individual activities. CPM is a simple and straightforward project method, and it can be used:

1. To find how long a project will take;
2. To identify the critical path;
3. To show the bottleneck and the critical activities;
4. To calculate the slack time to buffer certain activities.

CPM can be easily applied to various projects as discussed by Levy, et al. (32). However, CPM was developed for flow-type working process. It could tackle fairly complex projects with minimal uncertainty in the project completion times. For projects with higher uncertainties, which require a large number of design iterations, the CPM is usually less capable and applicable.

Since uncertainty is the nature of the process, more sophisticated methods are developed. The uncertainties should not be always regarded as the risks; instead, they can provide opportunities also. De Neufville, et al. (33) propose that "Uncertainty management is a particularly significant long-term foundation issue for planning, design, and management of engineering systems." They conclude that the management of uncertainties was to enable the design to evolve and adapt to new circumstances. Clausing and Frey (34) propose a CPM practice, which was designed to maintain the robustness of the system through detail design and manufacturing. They suggest performing the CPM analysis after the robust design to achieve optimized value. Kolltveit, et al. (35) suggest exploring opportunities embedded in the uncertain early project-planning phase, by allocating sufficient resources.

In the later 1950's, the US Navy improved the CPM to PERT, which includes a network model that allows for randomness in activity completion times. In addition to finding the critical path of a project, PERT predicts the beta distribution probability of the completion time before a specified date. Therefore, PERT provides a better tool for managing the risk. Booth, et al. (36) further extended the usage of the PERT method into production safety control. Since the PERT approach is developed based on CPM, it has an inherent problem: no process iteration is allowed in the analysis. Further, PERT analysis results are heavily dependent on individual judgment of the developer; the bias in the estimation is inevitable. PERT's assumption of a beta distribution of completion time is not always correct, and the accuracy of the prediction will be discounted. Also, PERT only estimates the possibility for the assumed critical path; it cannot effectively predict if the critical path is changed before the project completion. Therefore, the general evaluation for PERT is that it consistently under-estimates the expected project completion time.

In the 1970s, US Department of Defense initiated Earned Value Management (EVM). EVM is designed for the project management of cost, schedule, and technical performance. Obviously, EVM has the advantage of managing the project from multiple angles such as cost, schedule and progress. It can track the project in different actions or in item-oriented way. So it can help managers identify the bottlenecks in the development process. The weakness of EVM is that the bottleneck or critical parameter cannot be identified in the early stage of a project, while the correction cost is expected to be much high in the last stage of the development process.

Also in the 1970s, Mitstubishi's Kobe shipyard developed a design tool for process management known as QFD. Toyota and its suppliers have further improved QFD and have benefited from the practice. Eventually, a mature approach was created, called HoQ. The HoQ is composed of major attributes of product process. These attributes are customer requirements, engineering characteristics, business objectives, cost analysis, etc. The interventional relationships among these attributes are weighted according to their importance. Hauser and Clausing (19) concluded that the HoQ had successfully reduced the engineering changes in the Japanese automotive industry. In fact, Japanese automotive companies can address 90% of their engineering changes in the early design stage, 15 months earlier than their US competitors, with the help of HoQ. Olewnik and Lewis (37) further claim that the HoQ could greatly improve the internal communication due to the clearly defined internal relationship among different functional groups.

Many management tools have been developed and adopted for project management. However, the overall effectiveness of these above tools is still less satisfactory. The development of Microsoft 2000 was a typical failure example (38). Even though the phase-gate method was used in its project management, it could not effectively solve the uncertainties due to heavy design iterations. The final cost of the development was doubled and the product launch was delayed by 6 months.

Steward (39) developed a technique called Design Structure System (DSS) in 1981. It was originally designed for the analysis of design descriptions. A two-dimensional matrix, DSM, was designed to represent the structural or functional interrelationships of objects, tasks, or teams. Each task is assigned to a row and a corresponding column. Referring to Figure 3.8, the task sequence of row and column must be in the same order. A mark is placed in the column of the lower portion of the diagonal if there is dependency between the current task and previous tasks. The upper portion of the diagonal represents the feedback loop. If the result of the current task will change the performance of previous tasks, marks will be placed in the upper portion of the diagonal. DSM is most useful when tasks are listed in the order in which they are to be executed (Ulrich 22). In matrix partitioning, the DSM method changes the order of tasks based on the interaction among them. The results of DSM analysis can reveal which tasks must be performed sequentially, which tasks can be performed in parallel to save process time, and which tasks are coupled where process iterations are expected.

The most distinguishing function of DSM is the capability to integrate the design iterations into the project management process. Since the 1990s, research on DSM has been conducted more extensively. Eppinger et al. (39) adopted the DSM method to break the long feedback loops, divided the larger projects into several smaller size projects to facilitate the concurrent engineering practices. Cho and Eppinger (41) predicted the distribution of possible project completion times and costs with the DSM approach.

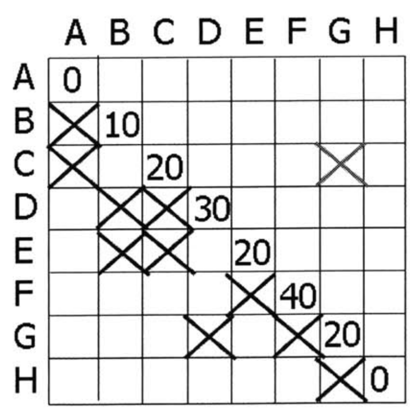


Figure 3.8 Sample of DSM

Since the DSM treats the planned and unplanned iterations equally, the analysis is still performed at static level, and it may mislead the resource allocation. Eppinger et al. (42)

proposed a generalized model called Signal Flow Graph (SFG) model. The new model is a hybrid of PERT and DSM. A signal flow graph matrix is created to list all the possibilities of iterations. Further, the human participation factors can also be included. The understanding of time-consuming design iteration can be greatly improved with this new approach.

In 1961, Forrester first introduced system dynamics management in his book, *Industrial Dynamics*. He presented System Dynamics (SD) modeling as "the way to combine both numerical and descriptive information into models that permit simulation of systems that are too complex for mathematical analysis." (43) It is a methodology developed for studying and managing complex feedback systems involved in business and other social activities.

The advent of advanced computer technology has greatly improved the SD practice. The SD has become "a rigorous modeling method that enables us to build formal computer simulations of complex systems that can be used to design more effective polices and organizations" (Sterman 44). Sterman (45) developed a system dynamic model to analyze the non-linearity and iteration in the human learning process, in which the barriers of the learning process are presented and analyzed. Lyneis (46) applied the system dynamic model in strategic project management including to:

1. Design the project;
2. Determine what indicators to measure, monitor, and exert pressure on;
3. Manage the risk;
4. Incorporate the learning from past projects;
5. Make mid-course corrections.

He concluded that compared with the system dynamic model, traditional tools are inadequate in dealing with the dynamic complexity of a project.
A typical system dynamic model (47) is composed of flow and stock, as presented in Figure 3.9. The stocks define the state of the system and the flows define the rate of

change in system states. The simulation provides a good understanding of the structure of projects, and how that structure creates behavior. It could be an effective guideline to lead people to change structure and develop robust projects.

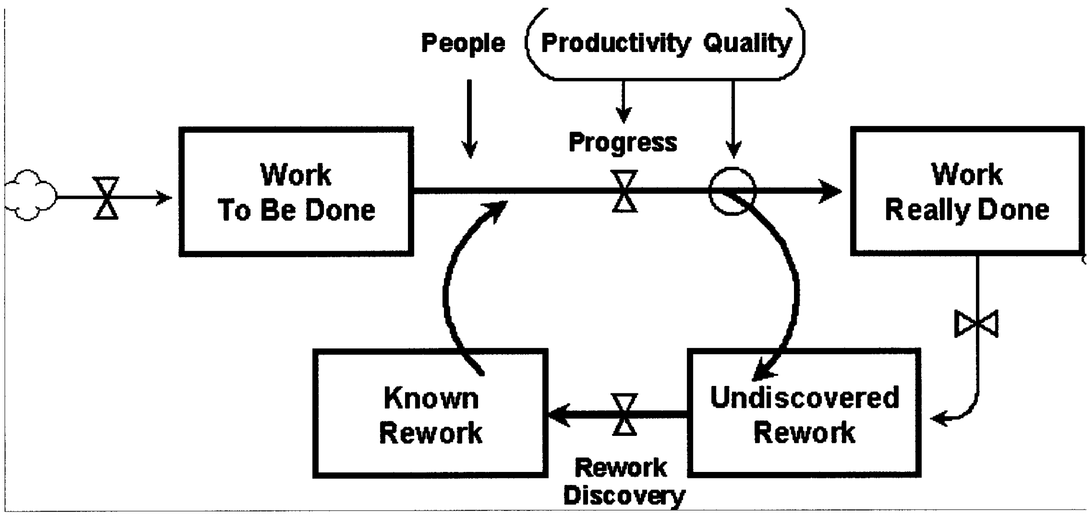


Figure 3.9 Example of SD Model

Chapter 4 Uncertainty Identification in Emission Technologies Engineering

In this chapter, the current ET engineering process is reviewed and the various sources of waste and uncertainty are defined. The research is mainly focused on external uncertainties, which cause large amounts of extra costs and ET has least control of them. A case review is provided to further understand the principles of lean engineering discussed in the previous chapter.

4.1 Uncertainties Review

The ET engineering service is always in the firefighting mode resulting from process uncertainties. Firefighting is more than an infrequently occurring phenomenon confined to individual projects and it is a de facto process occurring in almost all projects. It pulls resources away from an effective and mature process, with the consequence of higher engineering performance costs or waste. Repenning's research (48) shows a puzzle: "Everybody agrees that firefighting is detrimental to performance, yet, paradoxically, it persists." The origin of the firefighting is the uncertainties in the development process. Crawley (49) claims "… to solve the problem at current level, we must go one level higher." Since uncertainty is the source of firefighting, it must be defined clearly to move the firefighting dilemma away from the engineering process.

The Objective Process Matrix (OPM) is a comprehensive approach to systems architecture and lifecycle support. "The resulting OPM model is the central artifact of the system, product, or project that evolves and serves as a major reference to all the stakeholders throughout the entire lifecycle" (Crawley 50). It can be used to review the current ET engineering process.

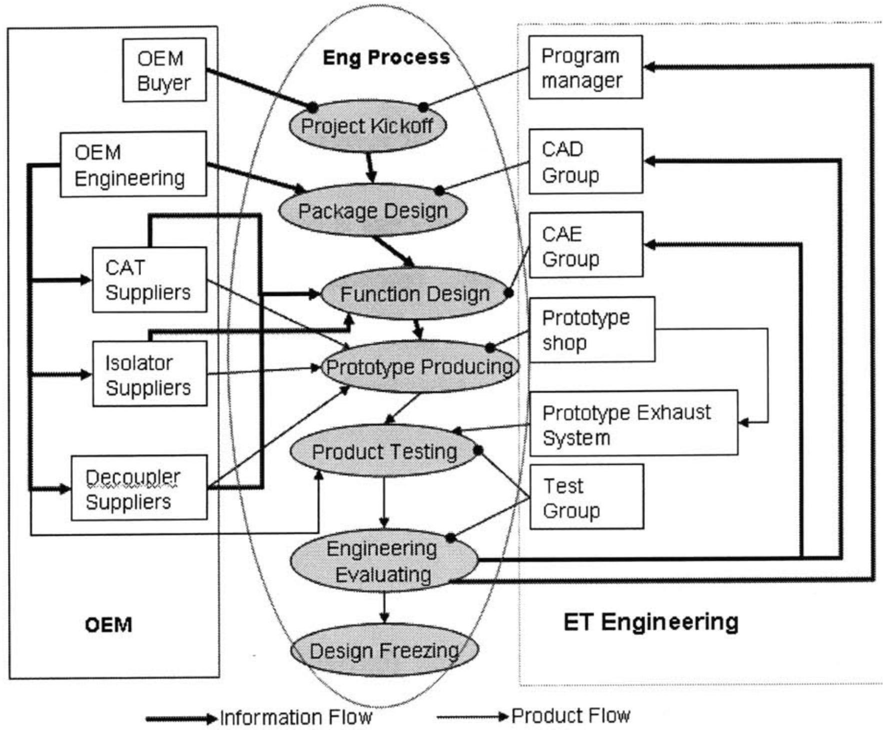


Figure 4.1 ET Engineering OPM

Figure 4.1 is an OPM model of current ET engineering. The ET engineering process is a high customer-oriented system and thus is a very vulnerable process. Three blocks are shown: 1) the central block represents all activities of theET engineering process; 2) the external block or the OEM activity block is on the left; and 3) the internal block or the ET engineering block is on the right. There are two different types of flow streams in this OPM: information flow and product flow. All information flows for design process are from the external block to the engineering process and engineering functional groups. All four major processes - package design, functional design, prototyping, and testing - need external the corresponding inputs. These inputs are normally beyond the control of ET engineering. It is the OEM's responsibility to make sure that all inputs are correct and delivered on time. Any uncertainty in these inputs will cause overall re-work or iteration, which will largely increase the PD time and cost. The "uncertainty" has a broad definition including a possible delay in delivering information, possible engineering change for more iteration, and possible wrong information for re-work and poor quality product.

The uncertainties existing in the inputs to the ET engineering process block are not under the control of ET. There are eight different inputs for the corresponding design process, including the various soft inputs (information) and hard inputs (testing vehicle). If the probability of uncertainty at each is P_i, the total probability of whole process uncertainty can be expressed as:

$$P_{process} = 1-(1-P_1)(1-P_2)\cdots(1-P_8) \tag{1}$$

If the annual probability of uncertainty at each input between the external block and ET process is assumed to be a constant value of 5%, and the internal uncertainty is assumed to be perfectly controlled ($P_{internal} = 0\%$), then the uncertainty level for the overall process will be estimated as 34% based on the calculation from equations 1 and 2.

$$P_{process} = 1-(1-5\%)^8 = 34\% \tag{2}$$

The resulting uncertainty level in the ET engineering process is very high and its influence on the normal engineering flow is diastrous. One third of its normal engineering activities are affected by the uncertainties, and if the uncertainties occur during the late stages of product design and development, the re-work or correction will be a huge cost or even the complete failure of the project. Even if the uncertainties are occurring in the earlier stage, they will still push the ET engineering service into the overloading, re-working, or firefighting mode. A five percent delay or uncertainty may not be an accurate number, but it is certainly a conservative estimate for most areas. The chance of delay in delivering a test vehicle can be as high as 50%.

To estimate the cost due to the uncertainties, the labor cost and duration of delay should also be considered. Assuming the labor cost is M units per day, the overall process possibility of delay N days is P_N, the expected cost can be obtained:

$$Cost = M * N * P_N \tag{3}$$

Figure 4.2 shows the cost due to uncertainties, where the labor cost is assumed to be 1 unit per day in this example. The probability of uncertainty varies from 1% to 10%, and the date required to solve uncertainties is in the range between 1 and 10 days. The cost reaches its peak at the 10^{th} day with 10% probability with a large slope. The longer it takes to solve uncertainties, the higher the cost will be. It further verifies that a later change in the engineering process will cost more to re-work or correct.

The above analysis is focused on external uncertainties only. Internal uncertainties also exist and can cause waste in the engineering process. They can be the result of errant operations of company, and usually they can be found in time and mitigated with experience and cooperation. Compared with the huge extra cost resulting from the external uncertainties, the cost from internal uncertainties is negligible. The effect of internal uncertainties usually can be anticipated in the project schedule. Several programs, such as AMPS, discussed in Section 3.1, have been launched internally within ArvinMeritor to reduce the uncertainties, eliminate the waste, and further reduce the cost.

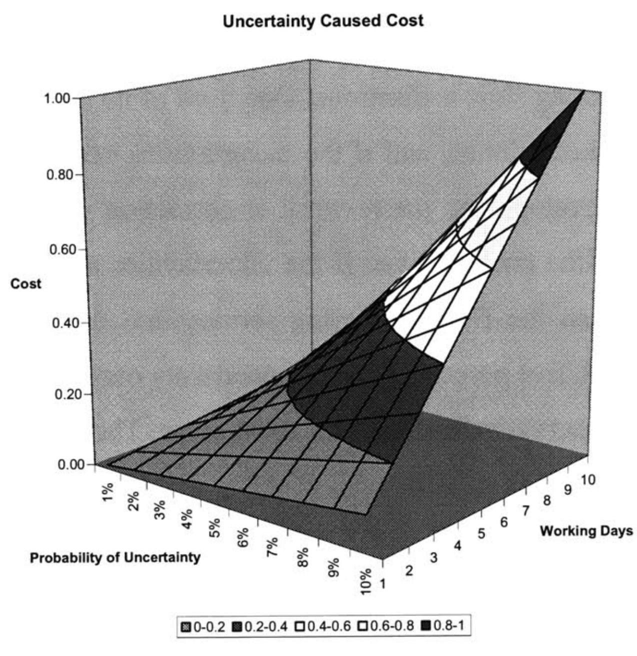


Figure 4.2 Uncertainty Cost Analysis

4.2 Uncertainty Source Identification

To better understand the uncertainties within exhaust system engineering, the various uncertainties can be classified as the internal uncertainties (mis-communication, technical deficiency, lack of management, etc.) and external uncertainties (late information, lack of support, late changes, misleading information, etc.). The uncertainties can also be defined as either the "Essence," which is inherent in the system and cannot be changed easily, or the "Accident," which is not inherent and can be changed or removed relatively easy.

Product differentiation is the trend of the automotive industry, and is driven by customer requirement. It is estimated that more than 100 new different models are to be launched in 2006 (51). Correspondingly, different new models will require different new engines and new exhaust systems. Combined with the existing models, one type of engine normally has several different exhaust systems to match. For example, the product portfolio of OEM A truck system includes gasoline/diesel pick up series, and light/heavy duty sport utility vehicle series. The corresponding variation of exhaust systems will reach as many as 50. This product differentiation will definitely increase the uncertainties from both internal and external sources including internal engineering and manufacturing, and the external OEMs and component suppliers. The internal uncertainties can gradually be reduced or eliminated by company operational programs or practices. ArvinMeritor's Business Excellence, Operation Excellence, and Design Excellence will be good initiates to handle these kinds of uncertainties. Because they can be changed, reduced or completely eliminated eventually, all internal uncertainties are "accidents." However, the product differentiation and its respective uncertainties are inherent in the nature of business; they are normally "essence," which will exist in the process for a long time and all manufacturers and suppliers have to live with them.

The external uncertainties include the wrong and late information from upstream suppliers or customers. In reality, ET's suppliers, like the decoupler suppliers and isolator suppliers, are mostly assigned or selected by the automotive OEMs, ET may be informed as to who its suppliers are for these two components when new business is offered. Under this situation, the OEMs are controlling and manipulating ET's major component suppliers including the catalyst converter, decoupler and isolator. ET's decisions are limited to the selection of raw steel material, hangers, pipes and other small commercial parts. It will be very difficult for ET to improve the system dynamic performance in terms of NVH and durability without the participation of decoupler and isolator suppliers. Usually, if there is structural failure or noise issue, ET can only work on its own portion of the system. No further improvement can be made beyond the scope of its own product. Both isolator and decoupler are commonly considered to be the best and most efficient way to reduce the vibration and to optimize the system structural dynamics. Any request for a design change of these two components needs to go through the OEM to locate the help, which will usually cause a time delay, miscommunication, lack of cooperation, and proprietary protection, etc. These "mudas" exist everywhere in this process. Under the current hierarchy system, the uncertainties imposed from OEMs and component suppliers are "essence." The transformation of "essences" into "accidents" needs cooperation between OEMs and suppliers. If ET becomes the whole exhaust system supplier including the catalyst converter, decoupler, isolator, muffler, pipe and hangers, the right components with right properties can be ordered directly, quickly and accurately. Many uncertainties in the process can be reduced or eventually eliminated by whole system integration.

In the current US automotive industry, all OEMs are practicing lean techniques in different areas. But most lean practices are focused on increasing the value of their own companies, and the lean practice has only been partially adopted at different levels in their organizations. Partial adoption can only generate the island phenomenon in the value stream. Under this island-lean practice, each stakeholder pays more attention to its own short time profitability. In the exhaust business, the buyers, OEMs, want to order the parts or components (such as converters, decouplers and isolators) from ET's suppliers directly, so OEMs have better control over their supply chain and will not be charged with overhead expenses, which happens if orders go through ET. As a result, OEMs achieve their financial goal but increase the uncertainties to the downstream exhaust system value stream. The large amount of extra costs caused by these uncertainties has to be taken on or balanced by its downstream stakeholders such as ArvinMeritor ET.

In the view of lean operation, a clustered or modulated supply system is required. (11) With a lean oriented supply structure, ET will take a leadership role in supplying the modularized exhaust systems. In this case, ET takes the full responsibility to OEM and the lower tier suppliers will report to ET directly. So ET would have better control of the external uncertainties, and the engineering cost to ArvinMeritor ET can be largely reduced.

To achieve this goal, support from the OEM is required. The OEM needs to turn over the controlling power on the lower tier suppliers to ET, which will result in better services including optimized designs, reduced PD cycles, reduced lead times, quicker times to the market, etc. To realize these latent supplier values in the whole value stream, it is necessary to lower the engineering uncertainty level. Statistics (52) show that 10% of the total supply chain cost is due to engineering changes. If the OEM and its suppliers can work together and set up a long-term collaboration to lower the uncertainty level in the value chain, the engineering cost of the whole value chain can be optimized, and all stakeholders can benefit from the value stream.

Figure 4.3 summarizes the uncertainties for exhaust system engineering development. The listed uncertainties are grouped in four categories: customer needs, structural designs, functional designs, and manufacturing tolerances. The time required by engineers to truly recognize the customer needs can be much longer than expected. The initial understanding of customer needs can be accurate, less accurate, or completely wrong. During the structural design, all parameters including the configurations and packaging requirements are subjected to change due to design iterations. The functional design is mainly the technology applications to meet various customer requirements. Either new or existing technology can be used as the baseline for new PD, but not all technologies are mature enough for a successful design. The uncertainties from the R&D and innovation will make the design process even more unpredictable, if the innovation itself is very risky. Manufacturing uncertainties mostly come from the production tolerances, which are inevitable. The objective for manufacturing quality control is to minimize the product quality deviation.

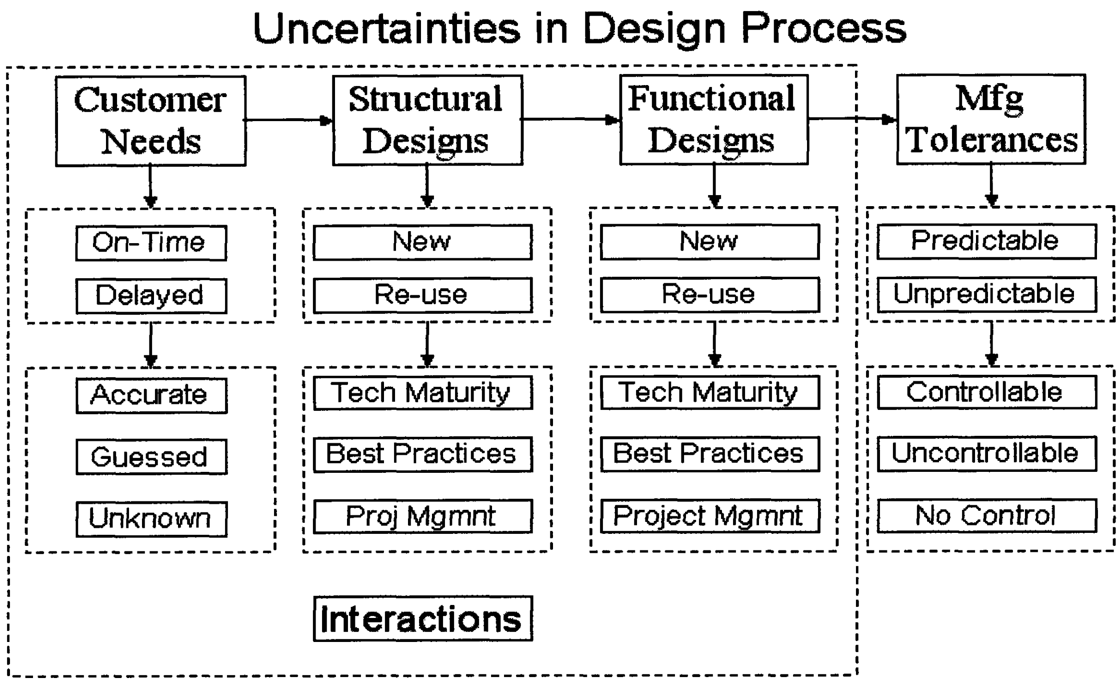


Figure 4.3 Uncertainties in Design Process

Compared with US automotive OEMs, Japanese automotive OEMs have achieved better engineering uncertainty management. For example, Toyota's Set-base approach (16) can greatly reduce uncertainties in the engineering information release. To further explain the uncertainties in the ET exhaust system, a case review is provided below.

4.3 Uncertainty Case Review - OEM A Truck Project

In 2003, the ArvinMeritor ET division won the largest project ever from OEM A in its 70 years' history. OEM A will purchase the exhaust system for most of its truck product lines from ArvinMeritor ET for the next four years. The total value of the order is expected to be significant to the ET annual revenue. A great deal of ET engineering effort has been dedicated to this project. So the uncertainty control in the process is extremely important and sensitive to the division in this case.

The OEM A truck project has a complicated product portfolio. The product portfolio of this project can be divided into different groups. Each group has several different sized engines. Table 4.1 is the product matrix. The complexity in the product portfolio is obvious, in which one exhaust system design has to accommodate the design of several engines. Many design iterations and customer engineering changes have occurred during the PD process. The uncertainties within the engineering process are seriously high.

Table 4.1 Exhaust System Product Portfolio for OEM A Truck System

Platform Bundle	Chassis Series	Engine Regular Production Options					
		E1	E1	E3	E4	E5	E6
Group #1	A	X	X	X			
	B	X	X	X			
	C	X	X	X			
	D	X	X	X	X		
	E		X	X	X	X	
	F			X			
Group #2	G						X
	H						X
	I						X
	J						X
	K						X
	L						X
	M						X
	N						X
Group #3	O		X	X	X	X	
	P			X		X	
Group #4	Q				X		

The total development cycle of this project has been limited to 36 months. To meet the customer product launch schedule, various techniques in advanced and lean engineering, such as CAE analysis, have been widely used during the PD process. However, the engineering development team has fallen into the firefighting mode since the beginning of the project. One of the reasons is the large amount of re-work caused by uncertainties within the process. What are the sources of the uncertainties in this process?

1. Uncertainties in the package design: The OEM A truck project took a large portion of the total ET engineering time in the package design. More than one - fourth of the engineering effort has been spent on various re-works. Both internal and external uncertainties contributed to the re-works. The internal uncertainties were caused by the design deficiency, and lack of sound engineering planning and strategies. Internal uncertainties caused about two-thirds of total re-works during this stage. The external uncertainties are the habitually and late engineering changes from OEM A. About 10% of the initial package requirements were changed afterwards, thus causing about one-third of the total re-works in this design stage.

2. Uncertainties in function design: The initial boundary conditions from customer and supplier are usually immature, such as the engine mass flow, vehicle and engine vibrations, and the decoupler and isolator designs. They are subject to changes during this design stage by OEM A and suppliers. Due to increased complexities in the project, the uncertainties in customer requirements are also higher, since there are so many systems and objectives involved in the functional design stage. OEM A did not have solid concepts of engine and chassis when ET moved into its functional design for the exhaust system. Due to the coupling effect, any change from the engine, chassis, decoupler, and isolator would affect the functional design of the exhaust system. As a matter of fact, there are about 5% engineering changes during this stage; these 5% engineering changes are measured based on engineering activities. These customer changes usually affect the design concepts of exhaust systems. Therefore, a huge amount of re-work will be required. For this OEM A truck project, at one point the truck project took 60% of the total CAE workload and 75% of the total Computational Fluid

Dynamic (CFD) workload. This 5% engineering changes from OEM A resulted in re-work of about half of the entire simulation efforts in this stage.

3. Uncertainties at late engineering stage: This OEM A truck project took a large amount of ET engineering test capacity. The likelihood of engineering changes is very low, since 90% of the product design is completed at this stage, and there is only about 1% of engineering change within this stage. The internal uncertainties at this stage are mainly the unexpected test failures of prototype, and the corresponding re-testing taking about 20% of the total working load. The main external uncertainty is the on-time delivery of a prototype for testing. More than 50% of testing vehicles were not delivered on time for this project. And about 10% of prototypes were not available when tests were ready. The delay in test parts caused extra idle time to the machine as well as to the manpower.

ET engineering has been heavily impacted by OEM A's traditional supply system. In fact, OEM A is still controlling ET's major component suppliers including the catalyst converter, decoupler and isolator. It is difficult for ET to optimize the whole system in terms of the dynamic performance, without the involvement of its two major suppliers. The system engineering of this exhaust system series requires instant, complete and accurate input from the suppliers, but the conveying system from ET to OEM A and to ET's suppliers caused more re-work and waste due to the time delay, miscommunication, lack of cooperation, and proprietary protection.

This OEM A case shows a typical uncertainty level during the PD process and its associated re-works. Some project management tools have been used in this OEM A truck project, but the effectiveness is very limited. The huge re-work and high engineering cost still exist. To achieve higher PD efficiency, ET needs to improve its process to reduce the internal uncertainties. In the meanwhile, ET needs to have an accurate damage evaluation due to external uncertainties in order to work with OEMs to address the external uncertainties.

Chapter 5 Value Stream Mapping & DSM Analysis In Emission Technologies

A value stream will be mapped for the current ET engineering process. Various lean engineering tools are to be applied to analyze the current ET value stream. The objective is to optimize the current process to make it more robust in response to the engineering uncertainties.

5.1 Review of Value Stream Mapping

In the automotive exhaust industry, the standard product launch procedure is a typical phase-gate process. It usually has six steps and five review gates. The six steps are planning, product design & development, process design & development, product & process validation, production launch, and feedback assessment and corrective action. The five review gates include project proposal, initial design, design verification, design release, process validation, and launch. Figure 5.1 shows a typical automotive PD process. The VSA for the exhaust system PD will be based on this typical PD process.

The five basic contents for the lean process, as defined by Womack and Jones (25) and (53), are value, value stream, flow, pull, and perfection:

1. Value: the capability to provide the customer with the right product, for the right price, and at the right time;
2. Value Stream: a set of actions that bring a product from concept to realization, from order to delivery, or from raw material to finished good;
3. Flow: movement through the value-creating steps seamlessly;
4. Pull: action to satisfy customer needs only, rather than forcing, or pushing, a product upon the marketplace;
5. Perfection: improvement of value, value stream, flow and pull in the business operations, continuously and relentlessly.

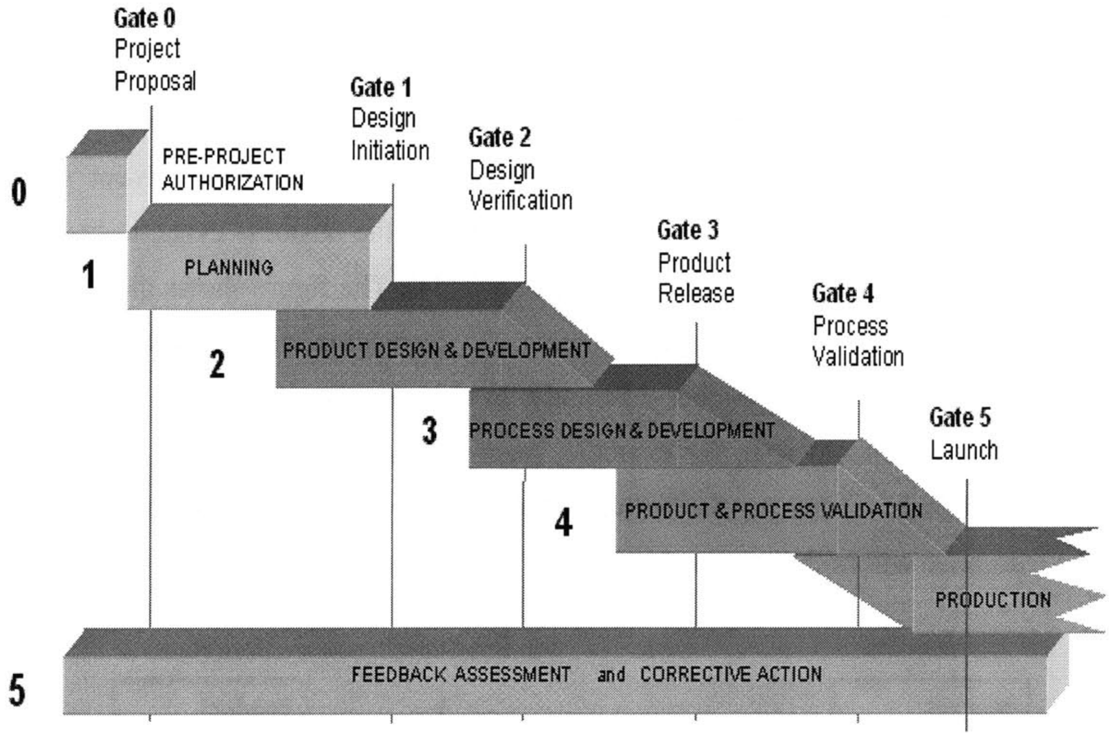


Figure 5.1 Auto Industry PD Process

The VSM/A is typically useful in rapid and low-cost improvement of PD. Many old processes worked very well in the past, but as time passed were burdened with an accumulation of special cases, quick fixes, firefights, and extra reviews. Even if they are still valuable at certain levels, but they will definitely slow down the current work process. As mentioned before, the value-added time of most PD efforts is about 12% of the total cycle time, and most efforts are spent in non-value added activities and task idle time. The early embarking on the lean engineering and implementations of VSM/A to the PD process can reduce the overall waste time by 50% - 90% (32).

The analysis and mapping of the value stream can reduce the wastes in the processes, enable flow, and lead the process towards perfection to a timely response to customer pull. If VSM/A is applied to the ET PD process, it means the on-time delivery of customer need regardless whether it is a new product, a modified design, or an adaptation of existing products. The basic principle of the VSM/A is to map the current state of the process, to apply lean techniques, and to create an improved future state vision of the process. In the proposed state, the non-value added tasks are identified and eliminated. This PD value will be effectively embedded in the product design and built into the VSA based design package. The PD value stream will then bring and fit the design package into a sequence with other value streams, such as the market development stream, realization stream, and deployment & support stream in the business cycle, to create the overall product lifecycle value shown in Figure 5.2 (54). The figure shows that each step of the business cycle from market development, PD, realization, deployment and support, will contribute value to the product separately. In the meantime, an earlier step provides value to its downstream step, for example, market development delivers value to PD. Also, the profit generated for the individual supplier or the value generated across the entire enterprise will both increase the value of the final product.

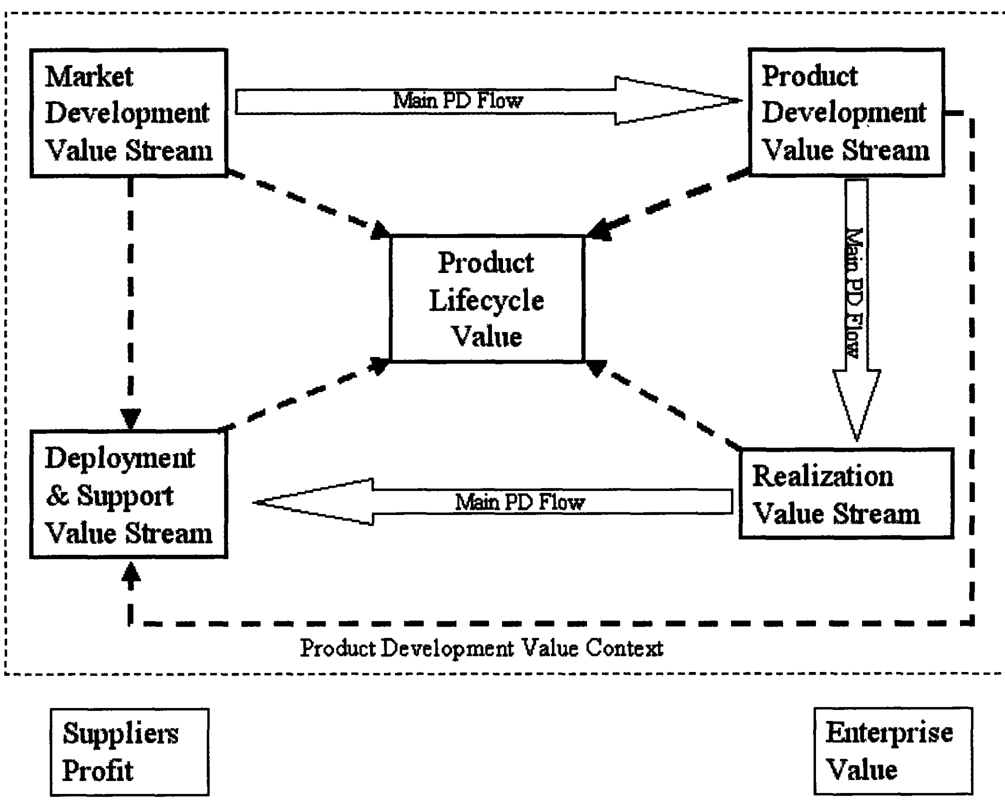


Figure 5.2 PD Value Context

Figure 5.3 shows how the tasks are adding value to the PD process. Information initiates from raw data, and it matures while it flows through the whole process. Not all tasks or data can add value to the flow and result in valuable wisdom, since there are various possible wastes and uncertainties, shown in Table 5.1. The resulting wisdom is dependent upon the knowledge application. The knowledge is based on a full assessment of information, and information can only be obtained from a well-organized raw data flow.

Table 5.1 Possible Wastes and Uncertainties in Exhaust PD Process

Waste Category	Descriptions of Wastes
Waiting	- Waiting for data, answers, specifications, requirements, test results, approvals, decisions, release, review events, signatures - Information created too earlier or unavailable - Late delivery
Transport / Handoffs	- Information incompatibility - Ineffective communication - Excessive data traffic, handoffs, stop and go tasks switching - Security issues
Overproduction / unsynchronized process	- Too many details - Over-dissemination of information - Unnecessary information - Poor synchronization as regards time, capacity and contents - Redundant tasks
Over processing	- Unnecessary serial efforts or tasks - Too many iterations - Unnecessary data conversions - Excessive verification and approvals - Unnecessary detail and accuracy, features and processes - Inappropriate use of competency & tools/methods
Inventory	- Too much information and excessive data storage - Poor configuration management - Queues on the critical path: excess capacity utilization, high system variability, and large batch sizes - Unnecessary testing equipment and prototypes - Complicated retrieval
Unnecessary Movement	- Required manual intervention - Lack of direct access - Information pushed to wrong sources - Remote locations - Information hunting - Reformatting
Defective Engineering Activities	- Deficient information quality - Conversion errors - Incomplete, ambiguous, or erroneous data and information - Poor testing and verification - Unclear engineering criteria
Reinvention	- Poor design re-use - Poor knowledge re-use
Lack of system discipline	- Incompetence and lack of training - Poor schedule discipline - Insufficient readiness to cooperate - Unclear rules, goals & objectives, responsibilities, and rights

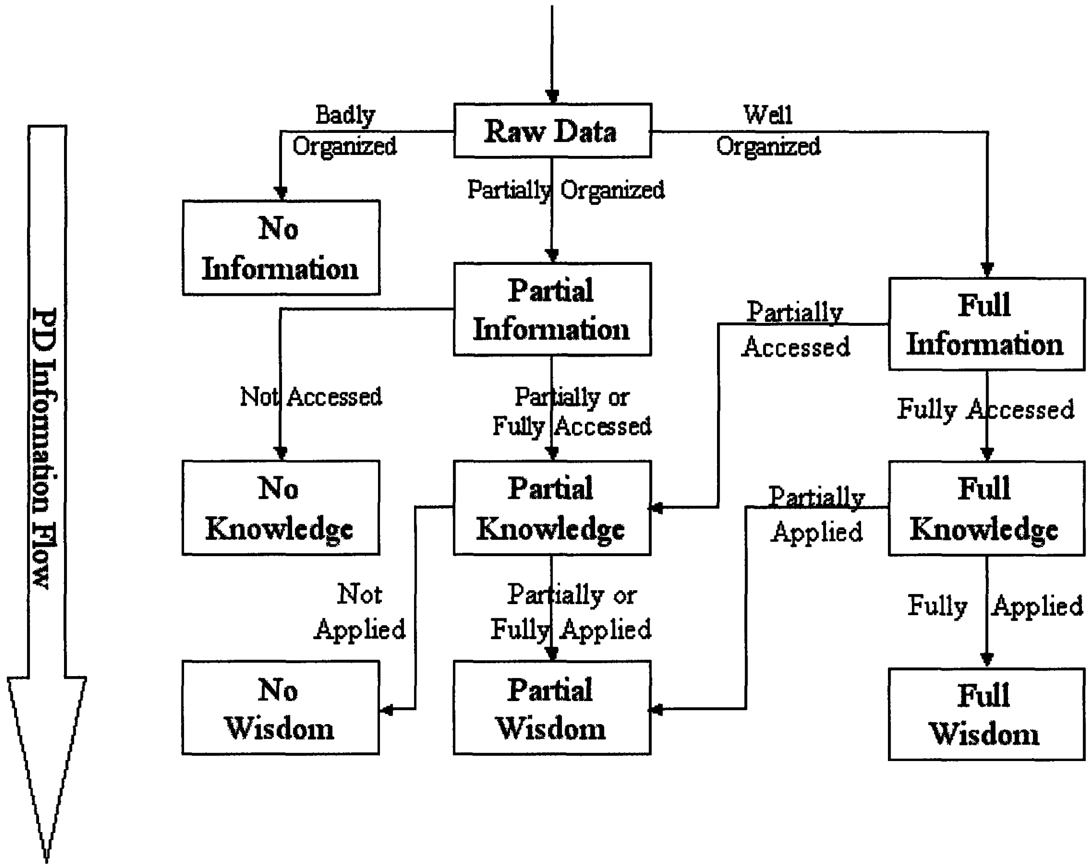


Figure 5.3 PD Information Progress

The automotive exhaust PD process flow, shown in Figure 5.4, can be used to better understand how the PD boundaries are determined, how product value is defined, and how the value stream delivers and increases the customer and company value through the PD process. Along with the value increase in the PD process, the perceived risk and uncertainties are also reduced.

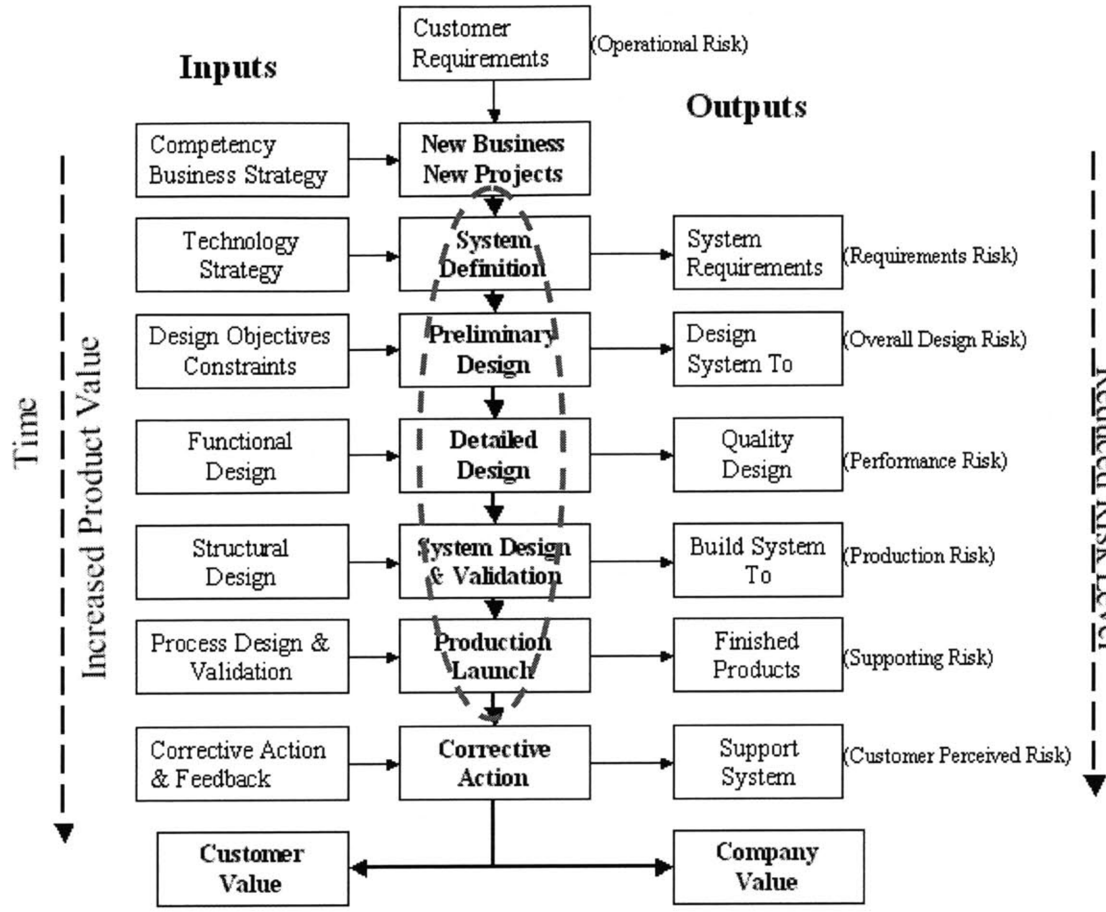


Figure 5.4 Automotive Exhaust Product Value Context

The activities shown with a red circle in Figure 5.4 are the routine engineering service processes for exhaust system design. A detailed list of ET engineering processes will be provided in the next section. A VSM will be generated to show the value stream of the ET engineering process.

5.2 Value Stream Mapping in Emission Technologies

Table 5.2 shows the 44 steps for the entire PD process and 40 of them for the engineering service steps within the ET engineering process. The VSM/A is focused on these 40 steps of engineering service steps. Following the order of process steps, the value steam map or the process flow of ET engineering service is developed, shown in Figure 5.5. The step sequence number of each step in Figure 5.5 matches exactly with that in Table 5.2.

Table 5.2 Typical Activities within ArvinMeritor ET PD Process

Full Product Cycle	ET PD Process	Process Tasks
1		Research market
2		Authorize quotation
3		Pre-Engineering
4		Win the bid
5	1	Package design
6	2	Design hanger
7	3	Locate hanger
8	4	CAE modal analysis on hanger
9	5	Select isolator
10	6	CAE model analysis on isolator
11	7	CAE resonance analysis
12	8	CAE Local Modes
13	9	Assembly hanger part
14	10	CAE/Test on hanger weld
15	11	Select base muffler
16	12	Initial test
17	13	Flow analysis
18	14	Prototype muffler
19	15	Sound quality design
20	16	On vehicle test
21	17	Design review for structure born (SB) issue
22	18	CAE / Test structure born (SB) issue
23	19	Finalize muffler design
24	20	CAE/Test on muffler design (weld)
25	21	Design pipe
26	22	Design Shield
27	23	Select flexible components
28	24	Select converter
29	25	CAE thermal analysis on converter
30	26	Assemble converter
31	27	CAE / Test on converter assembly
32	28	Full base system design and assembly
33	29	CAE/Test system flow
34	30	CAE / Test thermal
35	31	CAE / Test modal
36	32	Proving ground data acquisition decision making
37	33	Full system prototype
38	34	Data analysis
39	35	Full system test
40	36	CAE full system analysis
41	37	Design approve and release
42	38	Production launch
43	39	Customer vehicle test
44	40	Close project

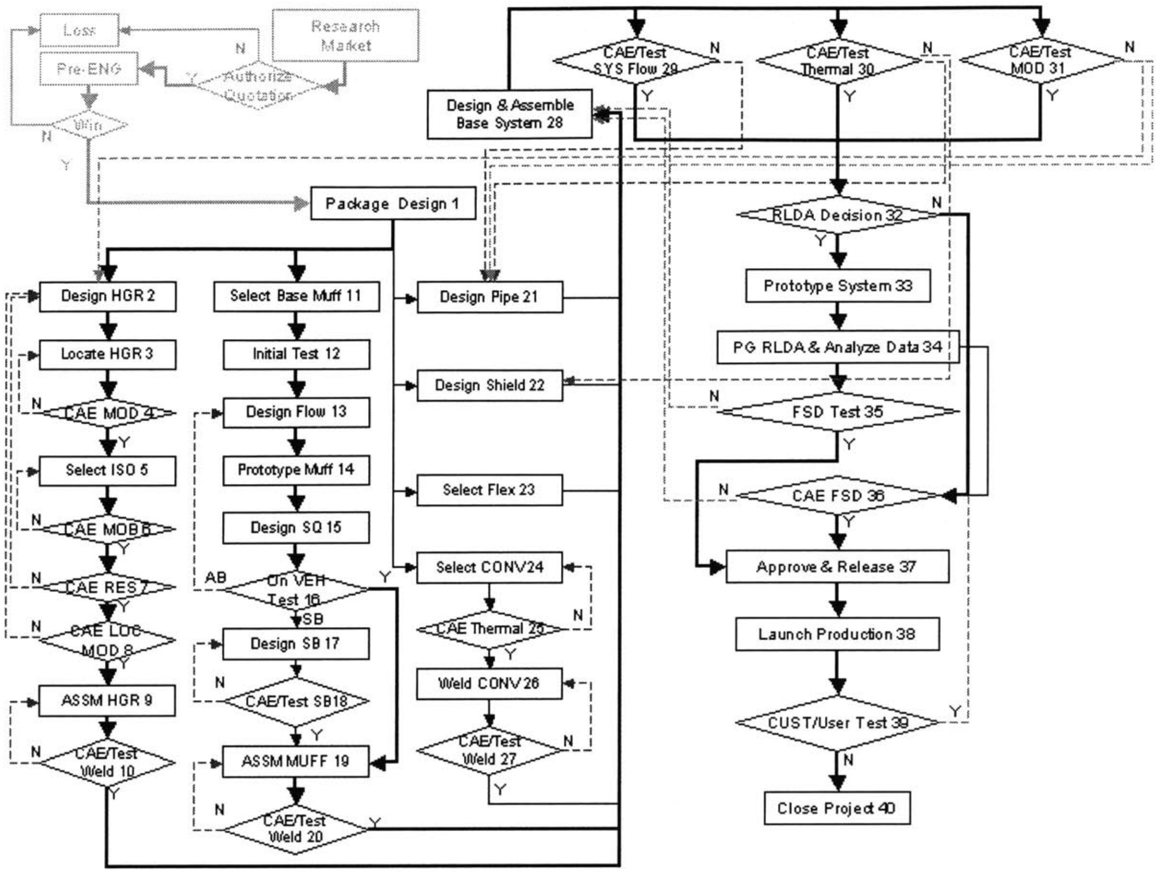


Figure 5.5 Process Flow Map for Exhaust PD

Based on a market study and competitor benchmarking, the available new business opportunities from customers are identified. In order to get an authorization for quotation from ET upper management, the program managers and product engineers need to study the customer requirement, manufacturing capacity, engineering capability, and financial limitation. After receiving authorization, the product engineer will ask supporting engineers to perform pre-design and pre-CAE. The results must be presented to the customer during the customer technical review meeting in order to win the business.

Once the business is awarded and the contract is signed, the product engineer will plan and schedule various designs, NVH development, CAE analyses and physical tests. The design can be divided into two groups, structure design and functional design. The objective of structure design is to design a system that can be fit to the vehicle and meet with durability and NVH requirements. The major tasks of structure design include full exhaust system route design, durability analysis, and NVH analysis. The functional design is focused on the functions of the exhaust system, whose main objectives are to tune the vehicle tail pipe noise and emission level to meet the government regulation. The tasks usually include back pressure control, legal noise requirement, sound quality requirements, etc. The design will not be released unless all customer requirements are satisfied.

The routine reviews for durability and NVH targets are conducted with the preliminary CAE. The design iterations for each subsystem are necessary in order to pass for the full system prototyping. The prototyped system is to be tested at the OEM proving ground to collect the dynamic responses, and the collected data need to be processed for a full system physical test or CAE analysis. If either the CAE or tests show structure failure or resonance problem, the appropriate design modifications will be required, even iterated from the very beginning of the project. These design modifications can be verified either by physical test or virtual CAE analysis. If the design passes both the physical test and CAE analysis, and the modification passes the CAE comparison, the design or modification will be finalized. The final design can be released from the engineering department for the production launch after certain documentation processes.

Referring to Figure 5.5, the light-colored tasks are not considered in this analysis, only the tasks or activities from the Program Managing to the Design Release, which are mainly the engineering services, are going to be studied. The major PD flow is indicated with the thicker arrows, and various iteration loops within the engineering services are represented with the colored arrows. The blue dotted line arrows are the local iterations or can be called planned iterations, while the purple, cyan, and red dotted line arrows are representing the serious unplanned iterations. These heavily colored unplanned iterations will cause re-work, delay and budget overrun, and they are normally caused by process uncertainties. A more sophisticated analysis by using the DSM method is recommended to re-organize the process, so the process can be improved.

5.3 DSM Analysis in Emission Technologies

5.3.1 DSM Model Development

Based on VSM of ArvinMeritor Emission Technologies PD, a DSM model is created in PSM32 (55), Figure 5.6. It is a task-based DSM model. The sequence number of each task follows the number listed in Table 5.2.

As introduced previously, the advantage of the DSM model is its capacity in analyzing the planned and unplanned engineering iterations. With reference to Figure 5.6, there are many marks in the upper portion of the diagonal which represent the iterations or loops within the ET engineering process. Some of them are planned iterations, such as those loops between two consecutive tasks, and thus they have been included in the original project schedule. Usually, a planned iteration will not cause a project delay or budget overrun. However, there are many unplanned iterations that may be caused by internal uncertainties or external uncertainties. For example, the feedback loop between Task 31 and Task 2 represents the case in which the baseline product cannot meet its design expectation, due to an internal design uncertainty. With the accumulation of engineering experience within ET division over the years, this iteration loop induced by internal uncertainty can be fixed relatively easily. However, the iteration between Task 39, the CAE full system analysis, and Task 36, the customer vehicle test, is a typical external uncertainty. If the failure is observed at this after-production stage, it requires most of ET efforts to be involved in order to solve the problem within an extremely short time frame. It would be a disaster to the whole program and the cost of rework would skyrocket.

The first step in the process analysis is to reorganize the current process flow based on the relationship among different tasks: it is called partitioning. The objective of partitioning is to find tasks that can be performed in parallel or in series. Figure 5.7 shows the partitioned result, where the process has been re-organized 7 blocks. The structure design and test is the largest performance block. Further analysis is required. Other development blocks are much smaller and relatively easier to be managed.

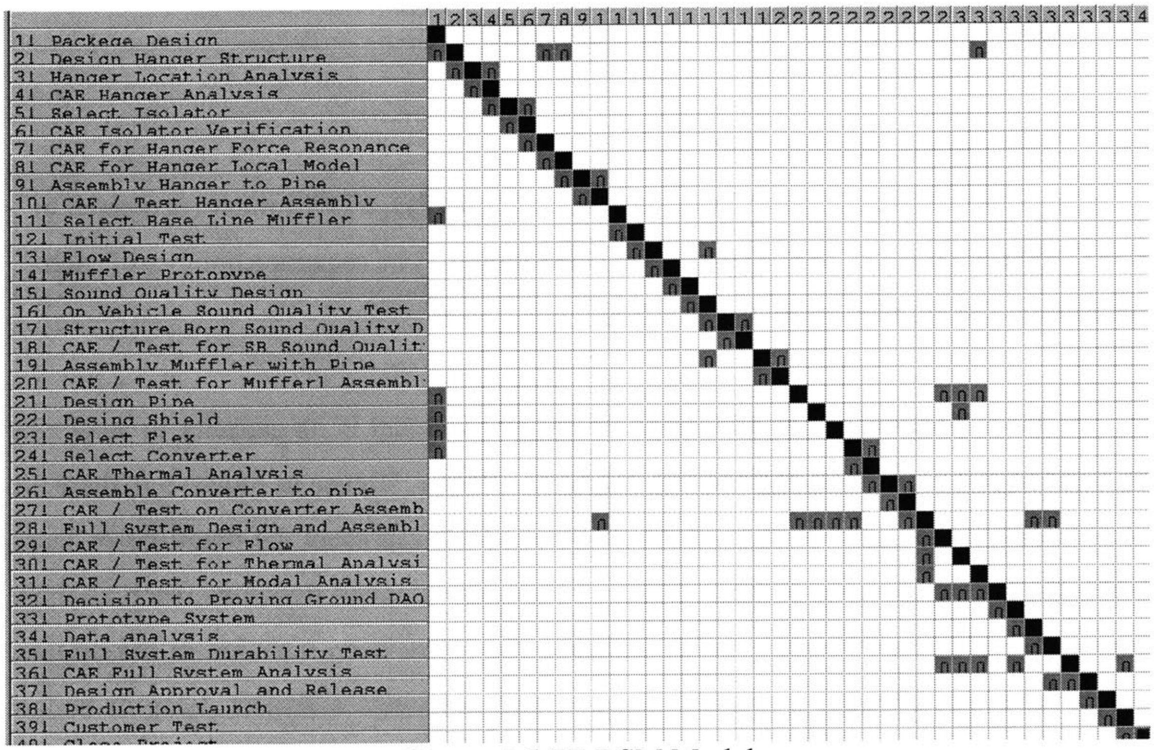


Figure 5.6 ET DSM Model

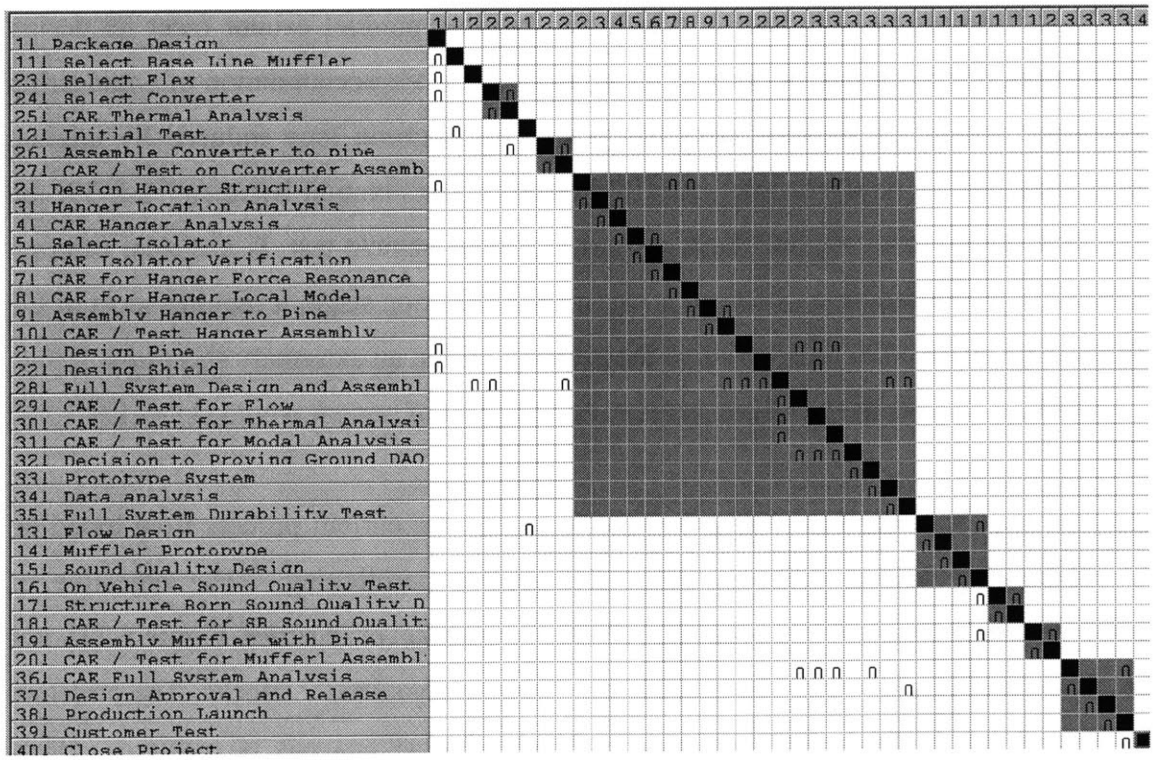


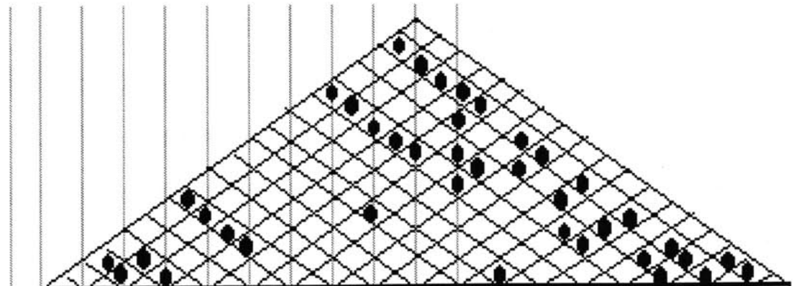
Figure 5.7 Partitioned PD Process

5.3.2 Prioritization with House of Quality

To perform further analysis, several iteration loops in the ET PD process need to be torn. All feedback loops in the ET engineering process will be prioritized based on their contributions to product performance or customer attributes. The prioritization is performed with HoQ.

The HoQ is started with customer requirements. The entire set of customer requirements for the exhaust system is used for the prioritization of the iterations within the ET PD process. The customer requirements can be ranked from 1 to 9 based on their importance with respect to the ET engineering process. "1" is the least important and "9" is the most important. For example, the customer requirement, Odor Discharge Level, is very important to a customer's emission control, but it is not so important to the ET structural and durability processes. The discharge level of odor is mostly determined by the catalytic converter, which is supplied by another supplier selected by OEM. Therefore, the Odor Discharge has been ranked as 2, of lower importance.

Changes have been made based on the traditional HoQ; the engineering design iterations are used as the roof of the house instead of the engineering characteristics. The body of the house is the relationship matrix, which indicates the relative importance of design iteration with respect to customer requirements. The roof matrix indicates the cross correlation among different engineering iterations. The foundation of the house is the evaluation results of the iterations. The most important iterations will be kept and the least important iterations will be torn consecutively. The torn results will be evaluated with DSM partitioning. The most critical process will be identified and the least critical steps will be marked.



Correlation Conflict Symbol - ●
Relation Matrix - Strong: 5
Relation Matrix - Moderate: 3
Relation Matrix - Weak: 1
Relation Matrix - None: 0

		Engineering Iterations																	
Customer Needs "WHATS"	**Weighted Ranking of Needs**	Hgr Loc Selection, Task 3 & 4	Hgr Mobility, Task 6 & 5	Hgr Resonance, Task 7 & Task 2	Loc Hgr Modes, Task 8 & 2	Hgr Weld Evaluation, Task 10 & 9	AB Noise Design , Task 16 & 13	SB Noise Design, Task 18 & 17	Muffl Weld Evaluation, Task 20 & 19	Con Temp Analysis, Task 25 & 24	Con Weld Evaluation, Task 27 & 26	Sys Flow Evaluation, Task 29 & 21	Pipe Temp Analysis, Task 30 & 21	Shield Temp Analysis, Task 30 & 22	Overall Hgr Evaluation, Task 31 & 2	Overall Pipe Evaluation, Task 31 & 21	FSD Test, Task 35 & 28	Full Sys CAE, Task 36 & 28	Cust Warrenty Test, Task 39 & 36
Leakage Requirements	6						1		1	1	1	3	3			1	1		3
Odor Discharge Level	2									1									
Catalytic Converter Light-off	8									5	1								
Sub-sys Comp Temp Limit	7						1		1	5	3		5	3		1			1
SB Noise & Vibratioin	9	3	3	5	3	1	1	5	3		1	3		1	5	3	3	3	3
AB Noise Level	9						5	1				3				3			
Leagal Noise Level	9		3	1	3	1	5	5	3			3				3	3	3	
Functional Design Package	4	1	3	1	3	3	1	1	3	3	3	3			3	3	3	3	3
Vehicel Theme	3						1					1							
Vehicle Squeak & Rattle	3	1	1				3	3	3	1		1							
Crashworthiness	2	1				1						1				1			
Corrosion resistance	4	1				1			3	1	1	1				1			1
Water Splash & Fording	1					1	1		3	1	1	1		3		1			
Engine Movement Accomodation	5	1	1	5		1		3			1	1			3	1	5	5	1
Structural Package Design	7	5	1	1	1	3		1	1	3	1	3	3	3	3	3	5	5	1
Durability Target	9	3	1	1	1	5	1	3	5	5	5	3	5	3	5	5	5	5	5
Importance Score		107	90	99	82	108	138	161	155	169	118	177	119	81	138	184	177	171	125
Importance Rank		3	1	2	0	3	6	8	7	9	4	9	4	0	6	10	9	9	4
DSM Partioning Sequence		2	1	1	1	2	4				3		3	1	4				3

Figure 5.8 House of Quality of ET Engineering Process

Figure 5.8 shows the HoQ for the ET structural and durability design iterations. The relative importance of the iterations against the customer requirements is ranked from 1 to 5. Rank 5 is the most important, 3 is moderately important, and 1 is the least important. The overall importance level of an iteration is calculated as:

$$C = \sum_{i=1}^{N} \left(R_i * S_i \right) \tag{4}$$

where C is total importance score of an iteration, R_i is importance level of a customer requirement, S_i is the relative importance level of an iteration against the corresponding customer requirement, and N is total number of customer requirements used in the calculation. The overall importance level of an iteration is ranked based on its importance score in a 0 to 10 scale. The importance of an iteration is defined based on its impact on on-time delivery of customer requirements. The durations and occurrences of iterations are implicitly embedded in the importance score. The iteration with the highest importance score will have a scale of 10, which means an important iteration. Similarly, the iteration with the least importance will be ranked as "0".

The least important iterations from 0 to 4 levels are consecutively torn and they are marked in the DSM model, shown in Figure 5.9:

1. 1st tearing includes the iterations with importance level of "0" and "1";
2. 2nd tearing includes the iterations with importance level of "2";
3. 3rd tearing includes the iterations with importance level of "3"; and
4. 4th tearing includes the iterations with importance level of "4".

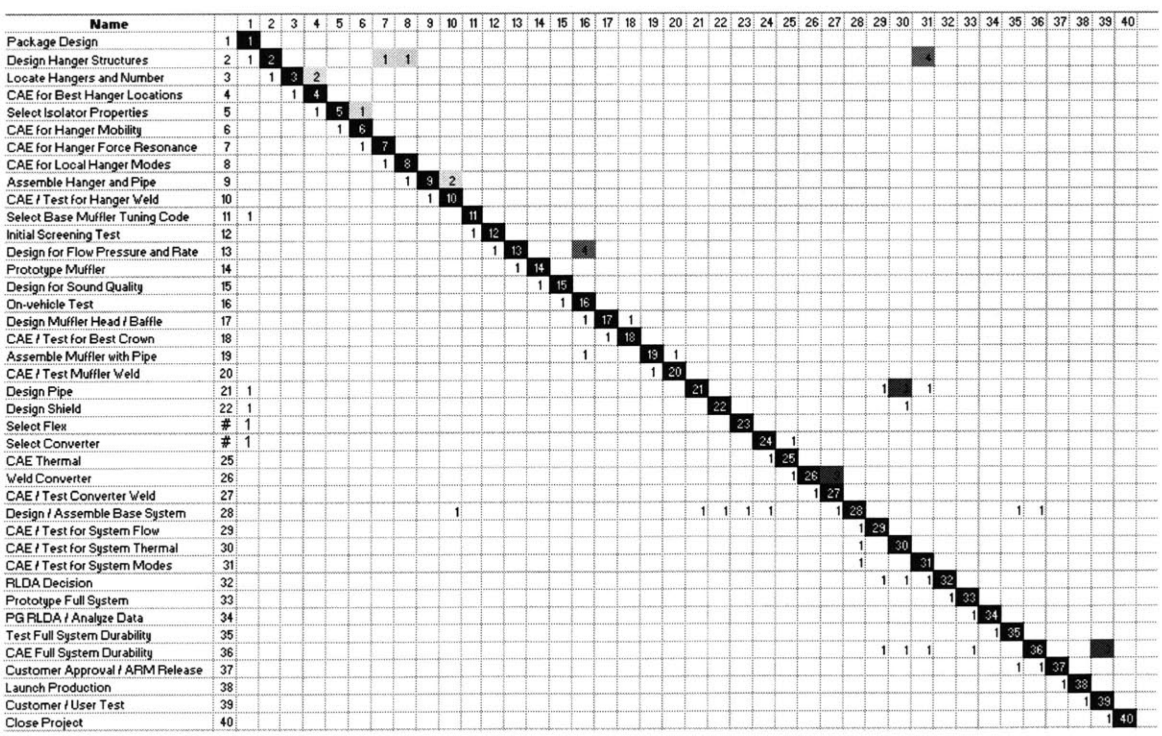


Figure 5.9 DSM Model with Tearing Sequence

5.3.3 DSM Partioning and Tearing Analysis

To analyze the process flow, it is necessary to gradually tear or remove the less important iteration. Based on the sequence shown in Figure 5.9, the partitioning results with different tearing options are shown in Figures 5.10 to Figure 5.13.

As shown in Figure 5.10, if only the iterations with importance levels at 0 to 3 are torn, the process improvement is not obvious, especially before the 3^{rd} tearing.

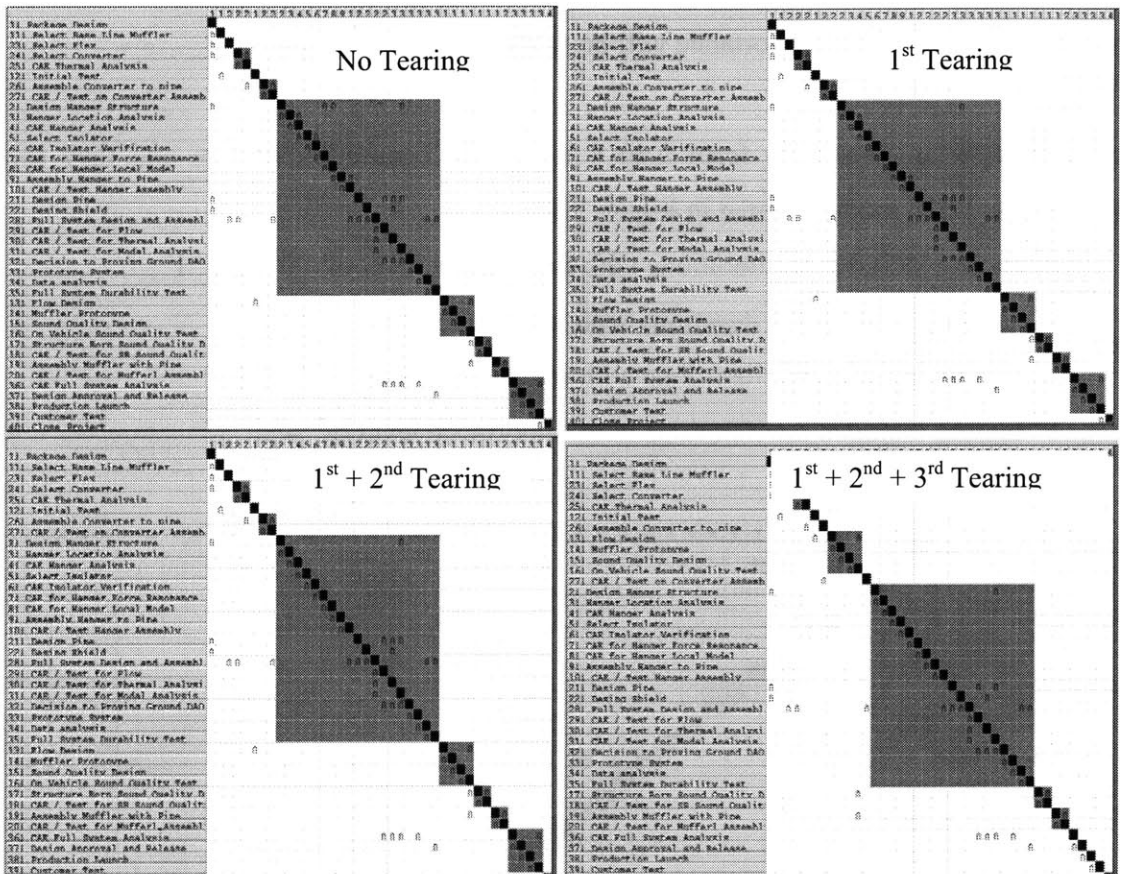


Figure 5.10 Partitioned Results Comparison (0, 1^{st} , 2^{nd} , 3^{rd} tearings)

Iterations up to 4^{th} tearing level need to be conducted in order to achieve the remarkable difference from the original process flow. Figure 5.11 shows the partitioning results based on all tearings from 1^{st} to 4^{th}. This result is promising: the structural durability process block is the only concern, and there are three other local iterations. However, too much effort on uncertainty removal needs to invested in order to avoid all 11 iterations from 0 to 4^{th} ranks, shown in Figure 5.8. There are a total 18 possible iterations within current engineering process, and it is very difficult to eliminate 11 iterations from 18 iterations simultaneously.

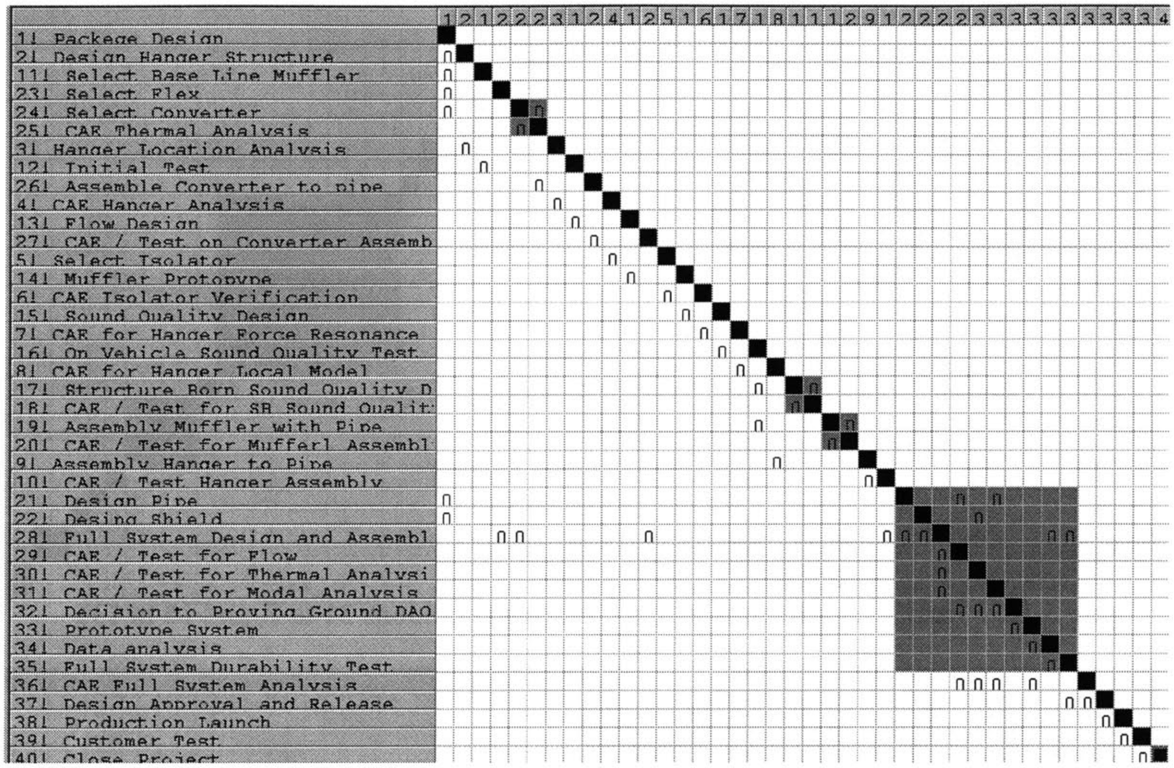


Figure 5.11 Partitioning Results with 1st, 2nd, 3rd, and 4th Tearings

Figure 5.12 shows the partitioned results with only two iterations (31 to 2 and 16 to 13) removed. The result indicates that the structural durability activity block is the biggest concern, and the hanger design is a very critical step in the whole engineering process. Further, there are five other less critical local iterations.

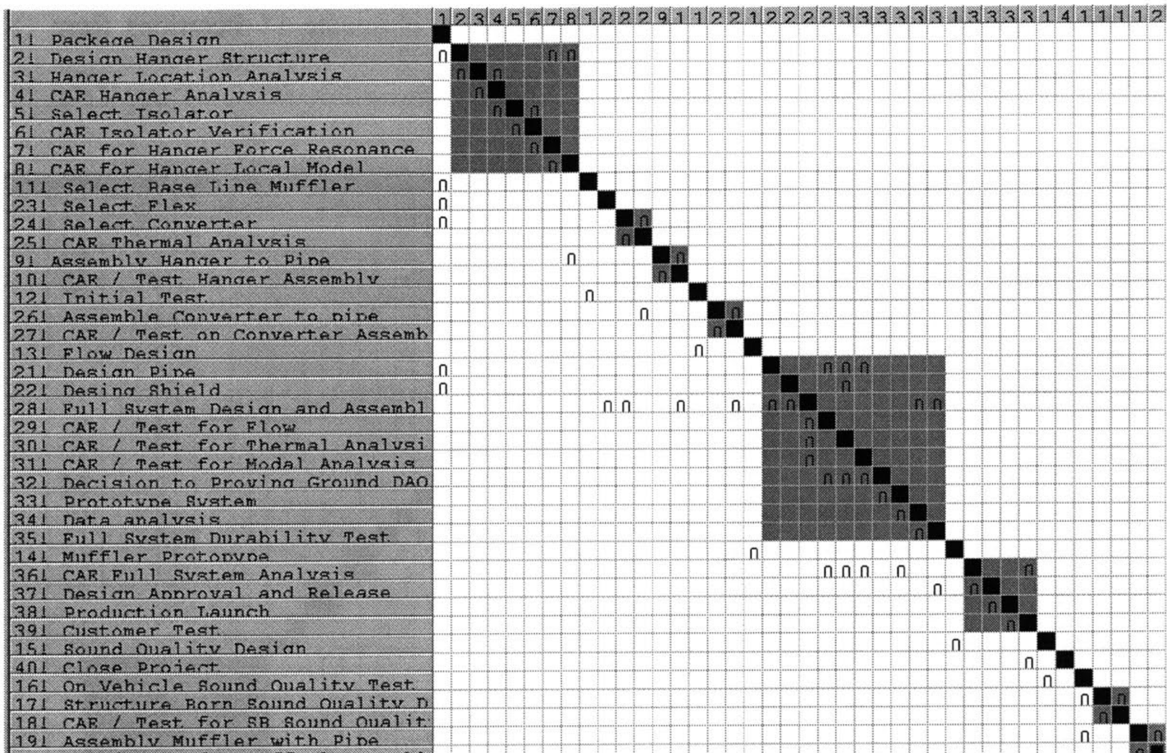


Figure 5.12 Partitioning Results with 4th Tearing (Iterations 31 to 2, and 16 to 13)

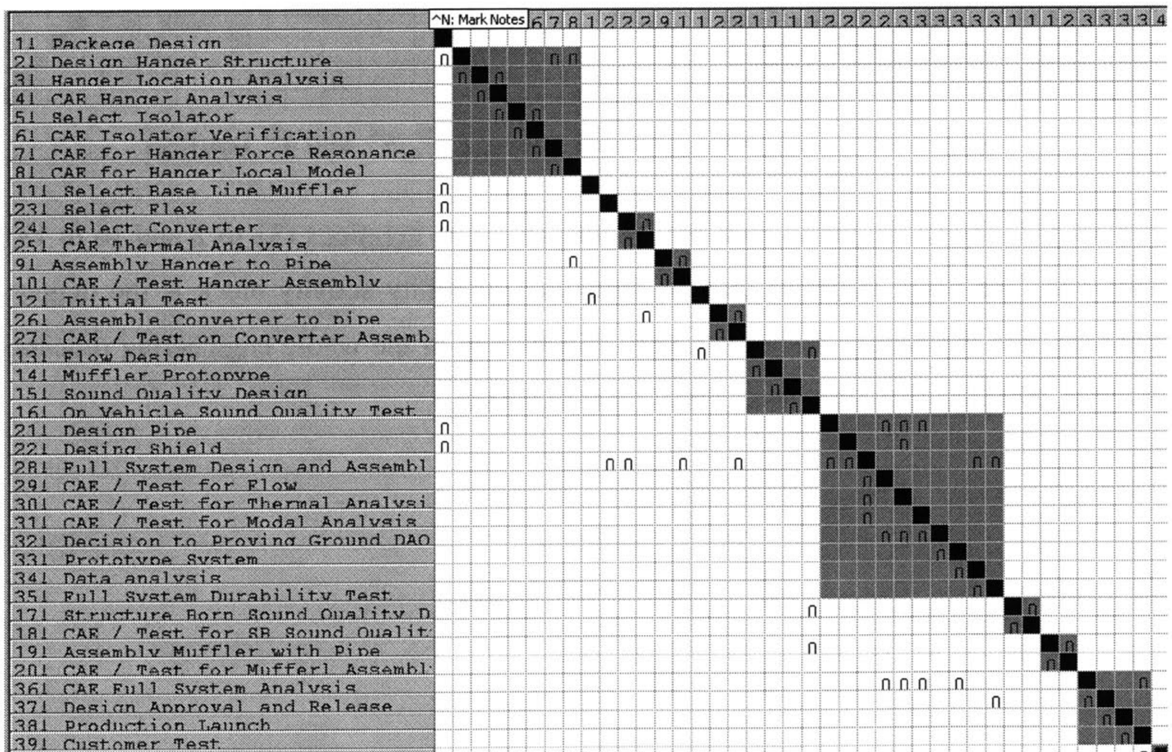


Figure 5.13 Partitioned Result with 4th Tearing (Iteration 31 to 2 only)

Figure 5.13 shows the partitioned result when only the iteration between Task 31 and Task 2 is removed. It can be concluded that:

1. The structural durability process block is still the most important; more effort may be invested to further improvement;
2. The hanger design process block is the second most important; appropriate attention needs to be paid in order to improve these steps and to prevent iteration back from step 31 to step 2;
3. The acoustic design is the third important process block, and needs to be finished before the structural durability block;
4. There are other five local iterations.

The above results are consistent with ET's current strategy for structural durability processes. Furthermore, ET should pay more attention to the hanger design process in the earlier stage. An optimized hanger design will largely eliminate the costly re-works. The re-works in other blocks are insiginificant to a critical process, and they are the planned design iterations.

Figure 5.14 proposes the most promised process, since it requires removing the iteration from Task 31 to Task 2 only. The new engineering process flow is simplified, in which both important and trivial processes are clearly indicated.

1. The tasks marked in blue are mainly for the hanger design. Further focus on these steps is recommended in order to prevent iteration from Task 31 back to Task;
2. The tasks marked in cyan are mainly for the acoustics design of the system. They determine the sound quality and legal noise level of the exhaust system;
3. The tasks marked in red are dominating the whole engineering process in the ET division. It is obvious that the structural durability block is the most critical area for further improvement;
4. The tasks marked in black are less critical tasks in the whole process in terms of contribution to PD process control.

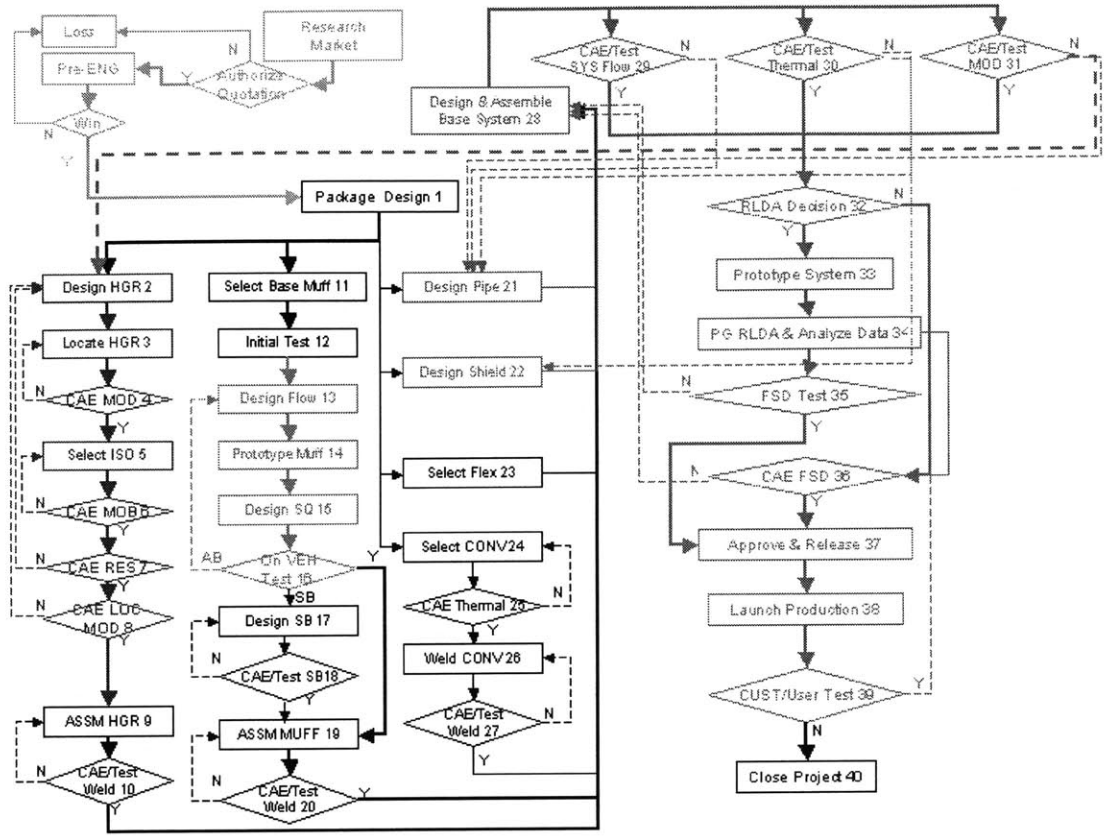


Figure 5.14 Proposed Process Flow

5.3.4 Imrpovement of the New Process – Case Study

The tasks in the process are usually uncertain in terms of actual task duration, re-work possibility, learning experience and impact on other tasks. To estimate the total duration of the process, and to evaluate the improvement of the suggested process, DSM Excel® macros are applied to a typical process with the OEM A project. Table 5.3 lists the durations of each task: minimum required days; likely required days; and maximum allowed days. Based on these duration values, a total of 100 random durations for one task are generated automatically by the Excel® macro. Each task has its corresponding probability and impact values, shown in Figures 5.15 and 5.16. The Learning Curve (LC), which is defined as the percentage of original task duration that is required when performing the task in subsequent iterations, is used as the multiplier to the impact. If an interation exists between two tasks, LC can be set as any none “0” value to define the portion of the current task to be repeated in subsequent iterations. If there is no iteration, LC is set to “0” since the current task will not be repeated in the rest of the development process at all. Table 5.3 lists three LC values for each task, the worst case, the medium case, and the best case. Since the iteration from task 31 to task 2 is the most detrimental step, the simulation will be focused on the evaluation of these tasks within this iteration. The LC values for task 2 to task 31 have been assigned with "1," "0.5," and "0.0," while the probability, impact and durations are using the same values. The worst case is to repeat 100% of each iteration (LC = 1) and the best case is to repeat 0% of each iteration (LC = 0). The actual improvement from the elimination of iteration from task 31 to task 2 can be estimated with the medium value (LC = 0.5).

Table 5.3 Task Process Duration

Original Sequence	Activity Name	Time (Days)			LC		
		Min	Likely	Max	Worst	Medium	Best
1	Package Design	10	15	20	1	1	1
2	Design Hanger Structures	3	5	7	1	0.5	0
3	Locate Hangers and Number	5	10	15	1	0.5	0
4	CAE for Best Hanger Locations	5	10	15	1	0.5	0
5	Select Isolator Properties	2	4	4	1	0.5	0
6	CAE for Hanger Mobility	2	2	2	1	0.5	0
7	CAE for Hanger Force Resonance	3	5	7	1	0.5	0
8	CAE for Local Hanger Modes	2	3	4	1	0.5	0
9	Assemble Hanger and Pipe	2	3	4	1	0.5	0
10	CAE / Test for Hanger Weld	3	5	7	1	0.5	0
11	Select Base Muffler Tuning Code	1	2	3	1	0.5	0
12	Initial Screening Test	1	1	1	1	0.5	0
13	Design for Flow Pressure and Rate	1	2	3	1	0.5	0
14	Prototype Muffler	2	3	5	1	0.5	0
15	Design for Sound Quality	2	3	5	1	0.5	0
16	On-vehicle Test	1	1	1	1	0.5	0
17	Design Muffler Head / Baffle	1	1	1	1	0.5	0
18	CAE / Test for Best Crown	1	1	1	1	0.5	0
19	Assemble Muffler with Pipe	1	1	1	1	0.5	0
20	CAE / Test Muffler Weld	1	1	1	1	0.5	0
21	Design Pipe	1	1	1	1	0.5	0
22	Design Shield	1	1	1	1	0.5	0
23	Select Flex	1	1	1	1	0.5	0
24	Select Converter	1	1	1	1	0.5	0
25	CAE Thermal	1	1	1	1	0.5	0
26	Weld Converter	1	1	1	1	0.5	0
27	CAE / Test Converter Weld	1	1	1	1	0.5	0
28	Design / Assemble Base System	5	10	15	1	0.5	0
29	CAE / Test for System Flow	3	5	8	1	1	1
30	CAE / Test for System Thermal	3	5	8	1	1	1
31	CAE / Test for System Modes	3	5	8	1	1	1
32	RLDA Decision	1	1	1	1	1	1
33	Prototype Full System	5	10	15	1	1	1
34	PG RLDA / Analyze Data	7	10	20	1	1	1
35	Test Full System Durability	20	35	50	1	1	1
36	CAE Full System Durability	5	7	10	1	1	1
37	Customer Approval / ARM Release	1	2	3	1	1	1
38	Launch Production	1	2	3	1	1	1
39	Customer / User Test	10	20	30	1	1	1
40	Close Project	1	1	1	1	1	1

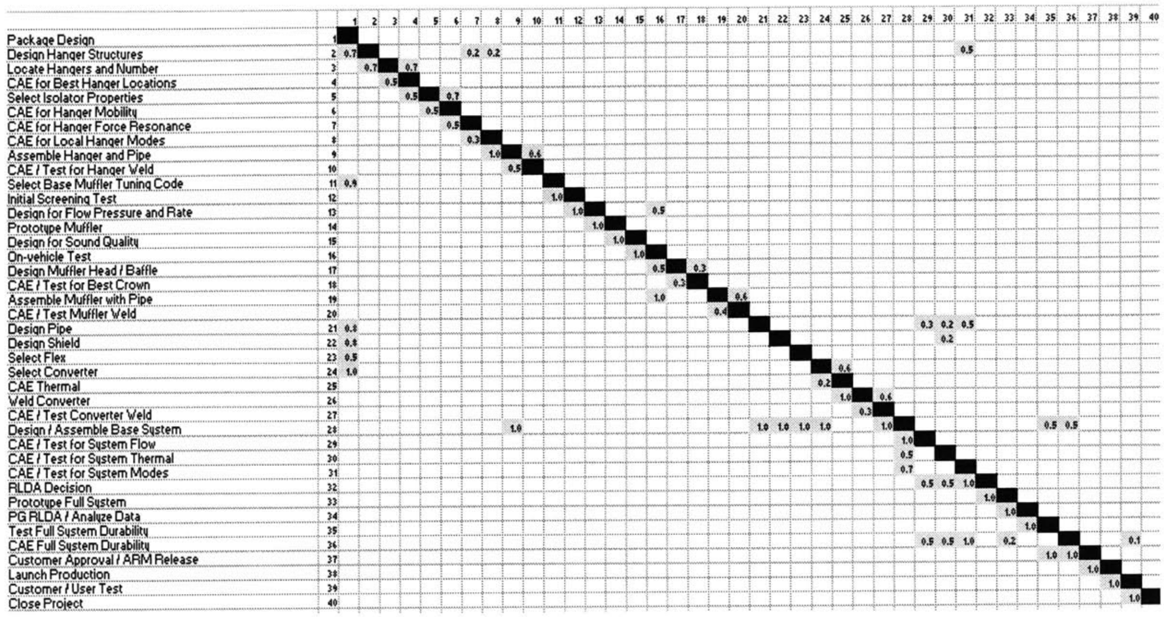


Figure 5.15 Task Probability

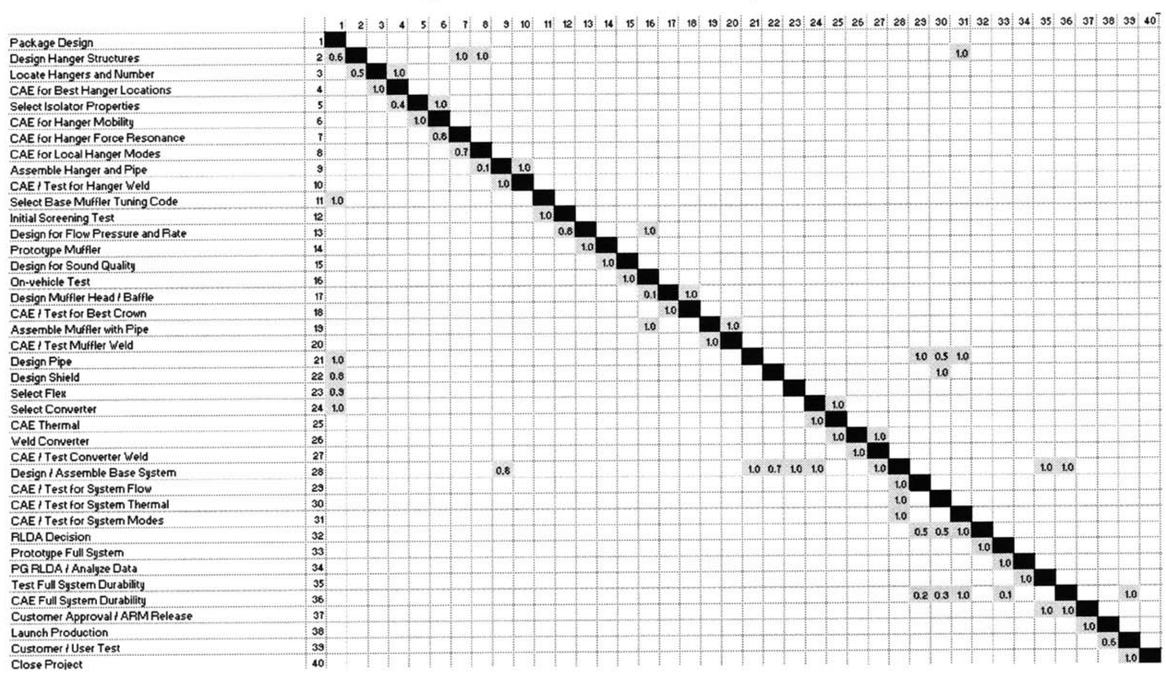


Figure 5.16 Task Impact

The histograms for different learning curve (LC) assumptions are shown in Figures 5.17 to 5.19. The 100 runs have been categorized automatically into 10 different bins, shown in Table 5.4. The Expected Values (EV) calculated with Equation 5 are used to compare the worst, the medium and the best cases. The best case (158 days) can reduce 16.4% of process time with respect to the worst case (189 days). The medium case can save 14 working days from 189 days to 175 days.

$$EV = \frac{\sum_{i=0}^{10}\left(Day_i * Frequency_i\right)}{\sum_{i=0}^{10} Frequency} \tag{5}$$

where i is the sequence number of each bin.

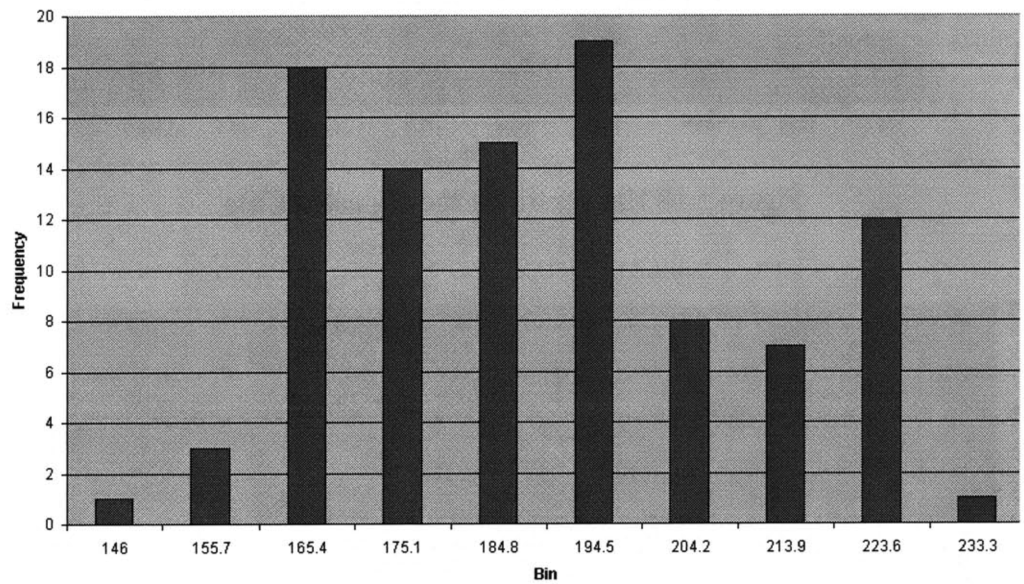


Figure 5.17 Histogram for the Worst Case

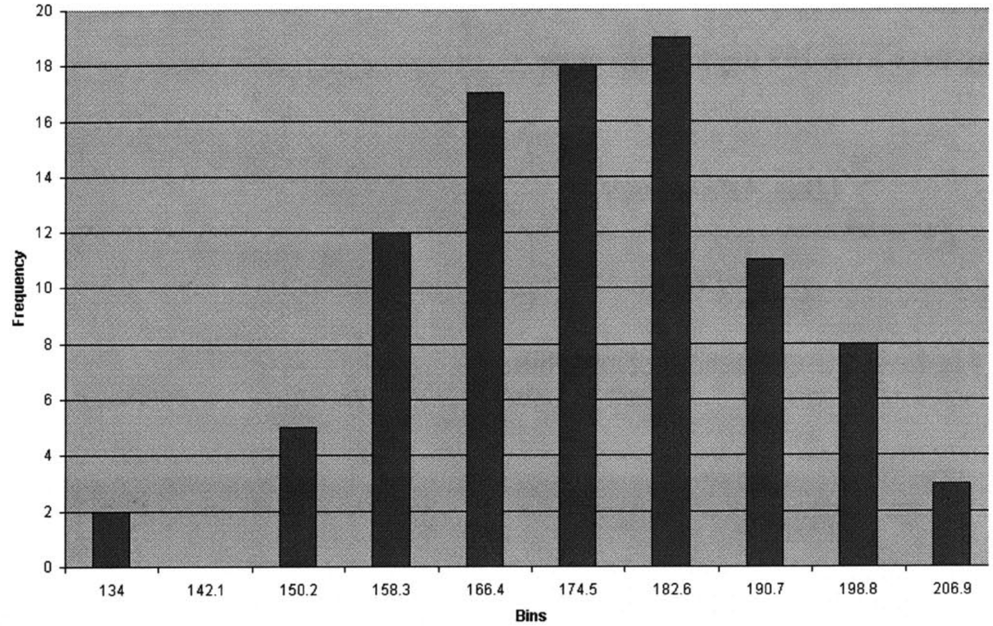


Figure 5.18 Histogram for the Expected Case

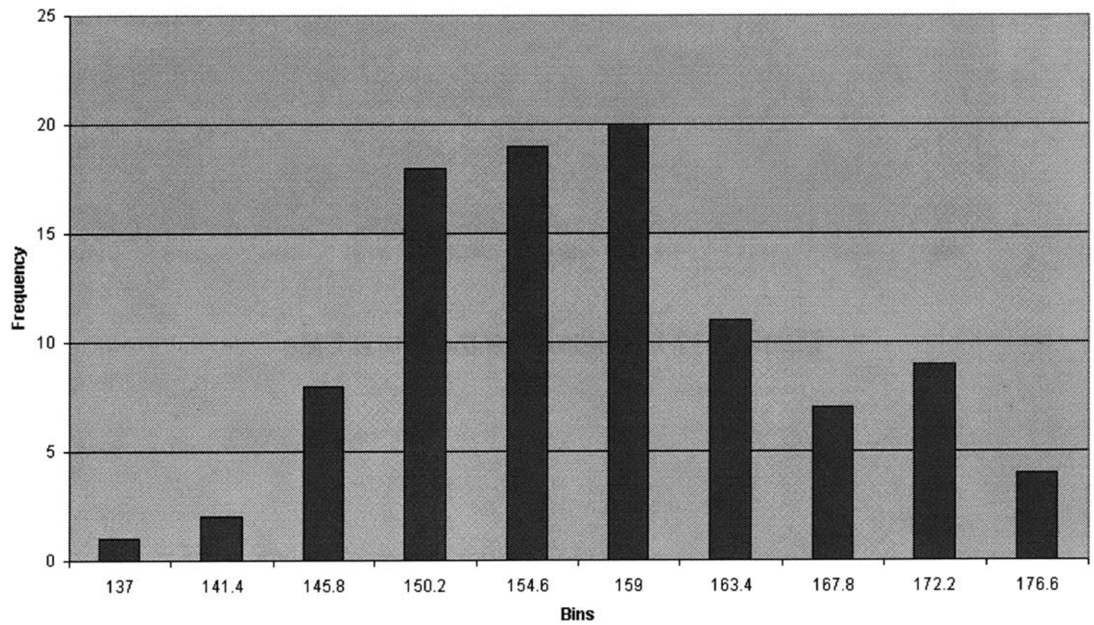


Figure 5.19 Histogram for the Best Case

Table 5.4 DSM Simulation Results

Bin Days - Worst	Frequency	Bin Days - Expected	Frequency	Bin Days - Best	Frequency
146	1	134	2	137	1
156	3	142	0	141	2
165	18	150	5	146	8
175	14	158	12	150	18
185	15	166	17	155	19
196	19	175	18	159	20
204	8	183	19	163	11
213	7	191	11	168	7
224	12	199	8	172	9
233	1	207	3	177	4
EV = 189		**EV = 175**		**EV = 158**	

5.4 Conclusion of VSM & DSM Analyses

The VSM, HoQ and DSM analyses have successfully identified the latent bottleneck in the ET engineering process. To improve the process efficiency, the uncertainty in the bottleneck step must be well controlled. The re-work due to these uncertainties must be removed in order to shorten the product development cycle. New PD process options can be proposed based on different efforts in uncertainty elimination. The actual process duration or improvement with iteration elimination can be simulated and evaluated.

The iterations caused by the engineering changes are not shown in this DSM model and the VSM of the process. In reality, the engineering changes can happen at any time during the process, and it is difficult to pinpoint these changes at an exact point. The engineering changes, whether they are in the early stage or in the late stage of the process, are all dynamics damaging the engineering process. A system dynamics analysis will be necessary to quantify, compare and evaluate the system dynamics within the ET exhaust engineering process.

Chapter 6 System Dynamic Analysis in Emission Technologies

An SD model is developed for the ET product development process to evaluate the system dynamic responses in terms of cost, schedule, resources, and quality, with respect to the customer engineering changes and other uncertainties in the system. The current engineering process, shown in Figure 6.1, is generalized to facilitate the process dynamic analysis. The SD results will quantify the current status of the ET engineering process.

The system dynamics can be defined mostly as the system uncertainties, and they exist everywhere in any process. Normally, they are the root-causes for engineering budget overruns, project delays, and product quality problems. In the practicing of lean engineering for the ET PD process, the main obstacle is the identification, reduction and elimination of the wastes and uncertainties. SD modeling and analysis is an efficient approach to show the relationships, responses, and effects of the system metrics. All the dynamic inputs or assumptions are based on the actual investigation and statistics.

6.1 The SD Model

An SD model, shown in Figure 6.2, is developed in Vensim® (58). The SD model is developed based on a simplified version VSM of the ET engineering process. Both the planned and the unplanned design iterations caused by engineering changes at different stages are included in this SD model. The changes are defined as the engineering changes from OEMs. They can happen at three different stages: the Package Design stage, the Function Design stage, and the Late Design stage, which is right before the design is released.

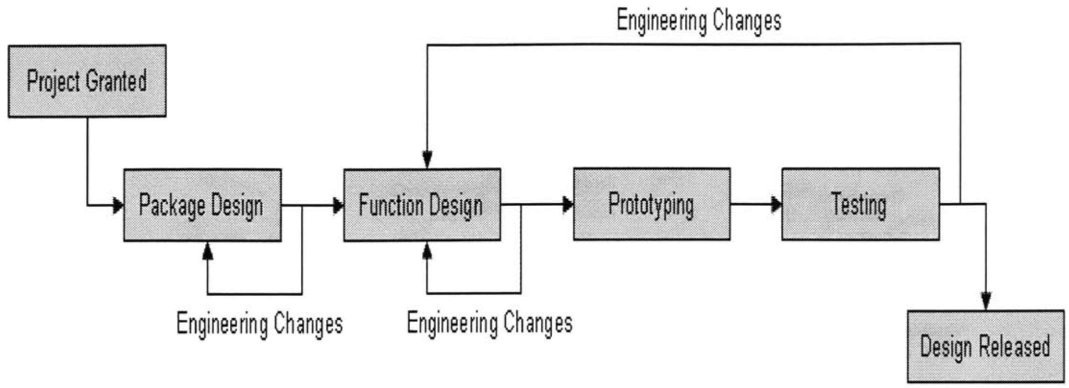


Figure 6.1 Simplified ArvinMeritor ET VSM

As shown in Figure 6.2, the SD model for the current ArvinMeritor ET engineering service covers the design steps from the kickoff of design to the design release, which corresponds to the steps shown in Figure 6.1. This SD model can be further divided into two sections: the engineering service process model and the firefighting model for resources and manpower allocation. Several concepts from Lyneis (48) and Repenning (59) have been implemented into this model. The definition of variables used in the model can be found in Appendix I.

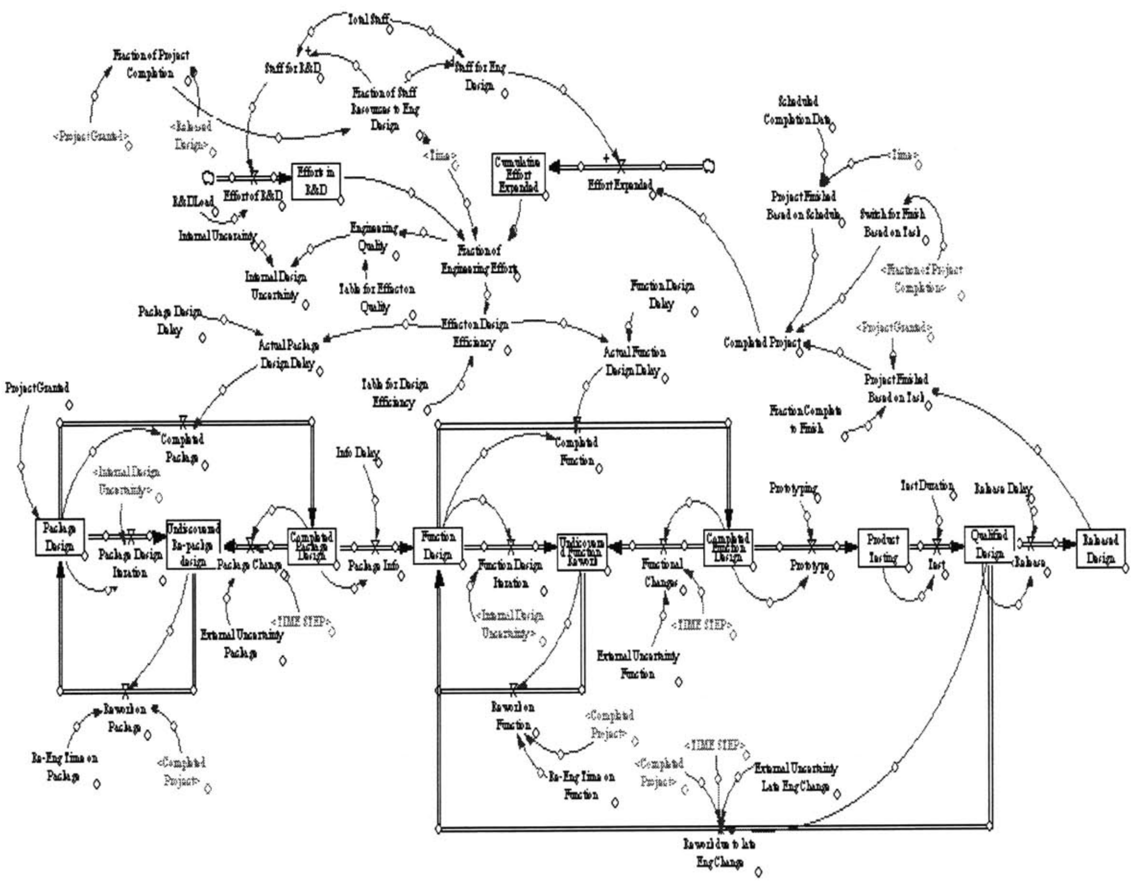


Figure 6.2 System Dynamic Model of ET Engineering Process

6.1.1 SD Model for Engineering Process

The engineering service starts with the package design. The completed package design is delivered to a functional design team for the product function design, such as the acoustic design. A prototype for the exhaust system will be built after the function design is finished. After the prototype is verified with various physical tests, the design can be released for production.

The internal uncertainties are caused by lack of design information, miscommunication, technical deficiency, etc. as discussed in previous chapters. Referring to Figure 6.2, internal uncertainties exist in both the package design stage and functional design stage. These internal uncertainties at these two locations are assumed to be related to the design experience. They are the response to the variables - designers' experience - and can be mitigated with earned design experience. It is assumed that the uncertainties level is in reverse proportion to the efforts made or design experience. More efforts or resources invested or more design experience will reduce uncertainty level and further improve the quality. Figure 6.3 shows the assumed S curve between quality level and earned experience. The X-axis, the input, is the earned experience. The Y-axis, the output, is the quality level.

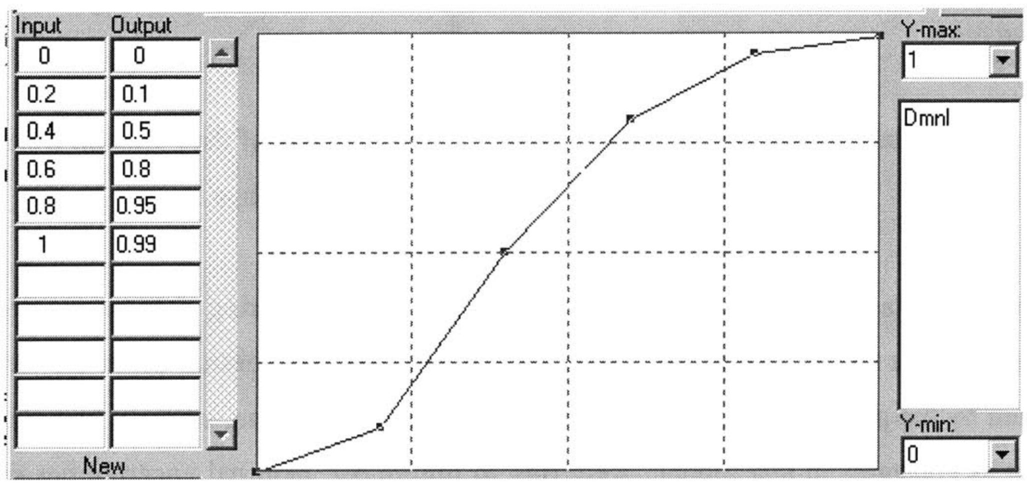
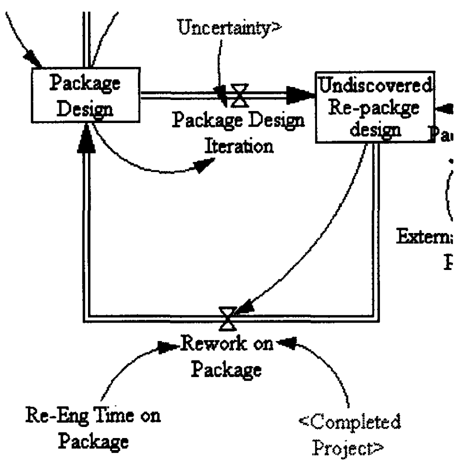
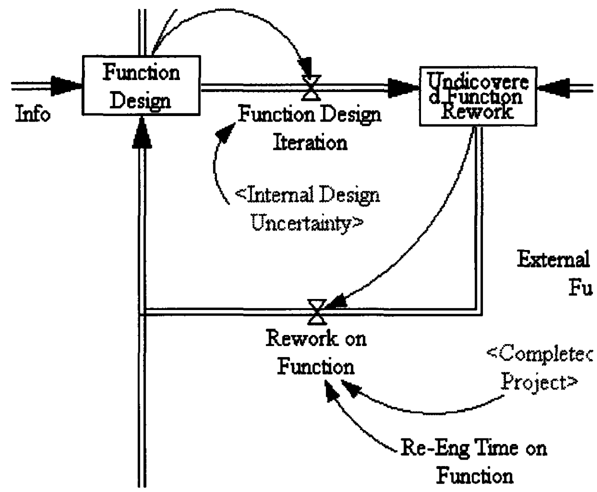


Figure 6.3 Quality Level V.S. Earned Experience

Two design iterations caused by internal uncertainties are shown in Figure 6.4. The definition of each variable can be found in Appendix I.

1. Package Design iteration: Package Design → Package Design Iteration → Undiscovered Re-package Design → Rework on Package → Package Design
1. Function Design iteration: Function Design → Function Design Iteration → Undiscovered Function Rework → Rework on Function → Function Design





(a) Iteration of the Package Design (b) Iteration of the Function Design

Figure 6.4 Internal Uncertainty Iteration Loops

External uncertainties are some disturbances such as the engineering changes required by customers, over which ArvinMeritor engineering team has less control. Since they are not affected by the performance of ArvinMeritor ET engineering team, external uncertainties are set as constants in this model. Referring to Figure 6.2, external uncertainties can be found at three locations, the Package Design, the Function Design, and the Late Design. Figure 6.5 shows an example of the iteration loop caused by an external uncertainty. Due to external uncertainties, customer requirement changes, the completed package design has to be re-designed. This re-design will increase the working volume of "Undiscovered Re-package design" which will add extra working loads to the design and engineering team. When there is no customer required engineering change, the variable, External Uncertainty Package, is set as "0". Therefore, no extra re-work will be added to the design team. The external uncertainty is defined as the ratio between customer engineering changes versus total customer engineering requests. The longest re-work design loop is caused by the "External Uncertainty Late Engineering Change." It means that the customer makes an engineering change right before the design is ready to be released, and the model will show how it will be a disaster to the PD.

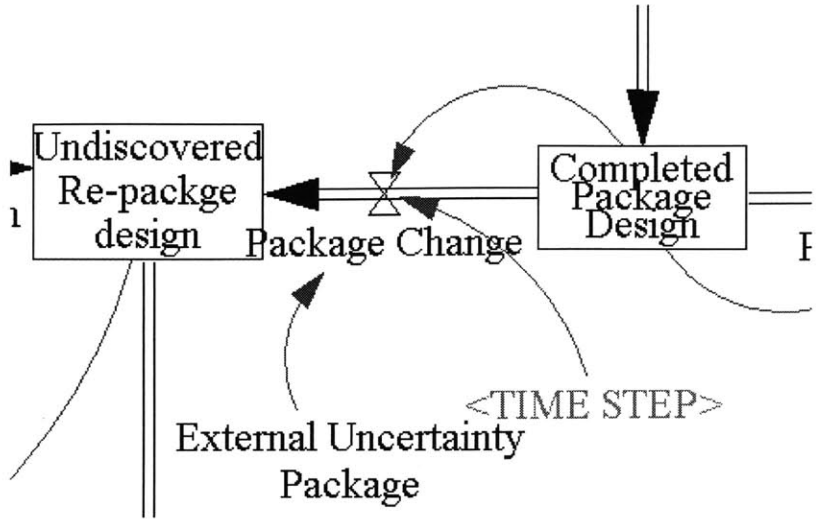


Figure 6.5 External Uncertainty Loop

6.1.2 SD Model for Resource Allocation

Effectively allocating human resources is always a challenge to the project management. The staff needs to be assigned between engineering support work and R&D activities. The engineering support usually has priority since the company needs routine business to keep running. However, R&D activities represent the future. They determine the future of the company. How to well organize the resources to cover both activities is always a challenge to management. The SD model, Figure 6.6, of staff allocation shows the shifts of resources under different conditions. The basic concept is from Repenning's firefighting model.

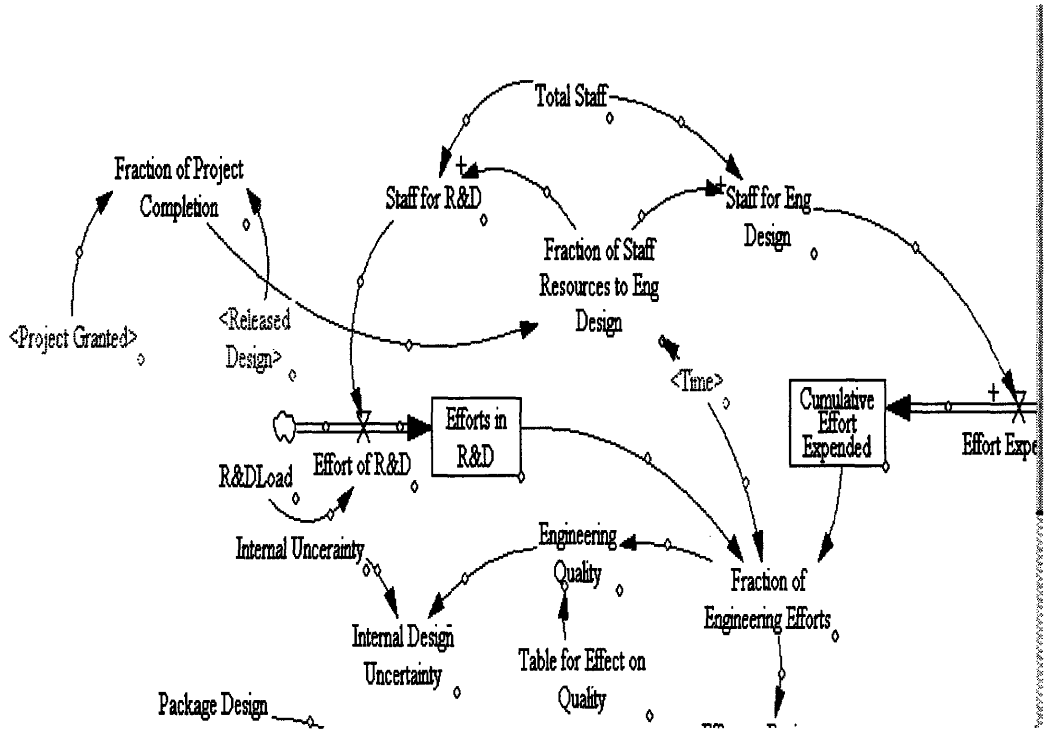


Figure 6.6 SD Model of Staff Allocation

Total available staff is fixed in this model. Staff allocation is determined by the "Fraction of Project Completion." Since the routine engineering work usually has higher priority, more staff will be involved in engineering design work if the completion of project is low. If the completion of the project is high, more staff will be released from design work and allowed to invest more time in R&D activities. Further, the Fraction of Engineering Efforts, in Figure 6.6, is the ratio of efforts invested in engineering design work and R&D activities. This ratio shows how much effort has been dedicated to the engineering design work. More effort dedicated to engineering design work means more earned experience. The earned experience will increase the quality, Figure 6.3.

The Fraction of Engineering Efforts also affects the efficiency of design. If more experienced manpower can be dedicated to a task, an increase of working efficiency is expected. Referring to Figure 6.7, the delays at both package design and function design will be reduced if more experienced manpower is invested in the engineering design process. The increase in efficiency is determined by the efficiency curve shown in Figure 6.8.

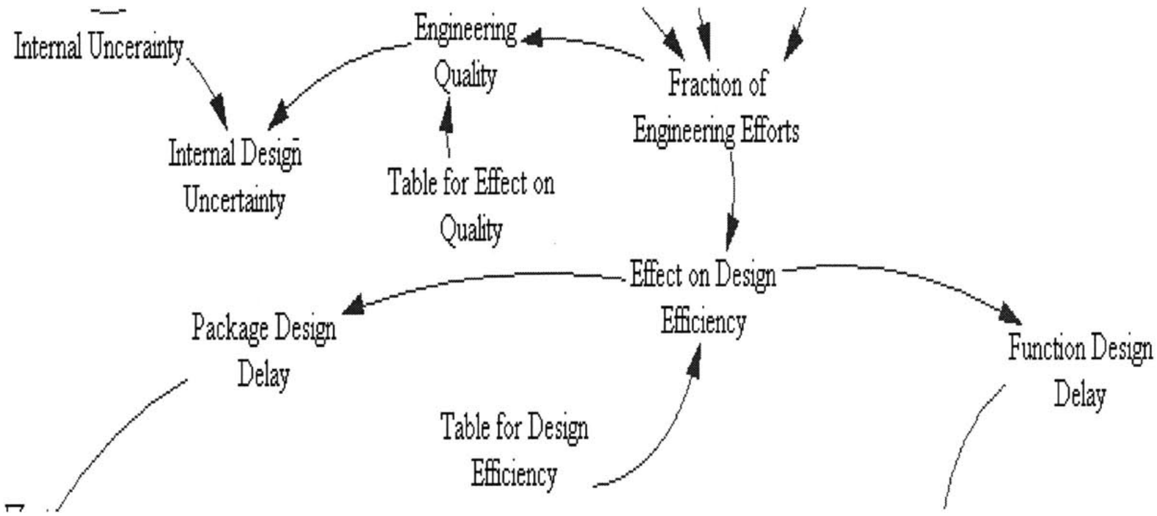


Figure 6.7 Efficiency of Design

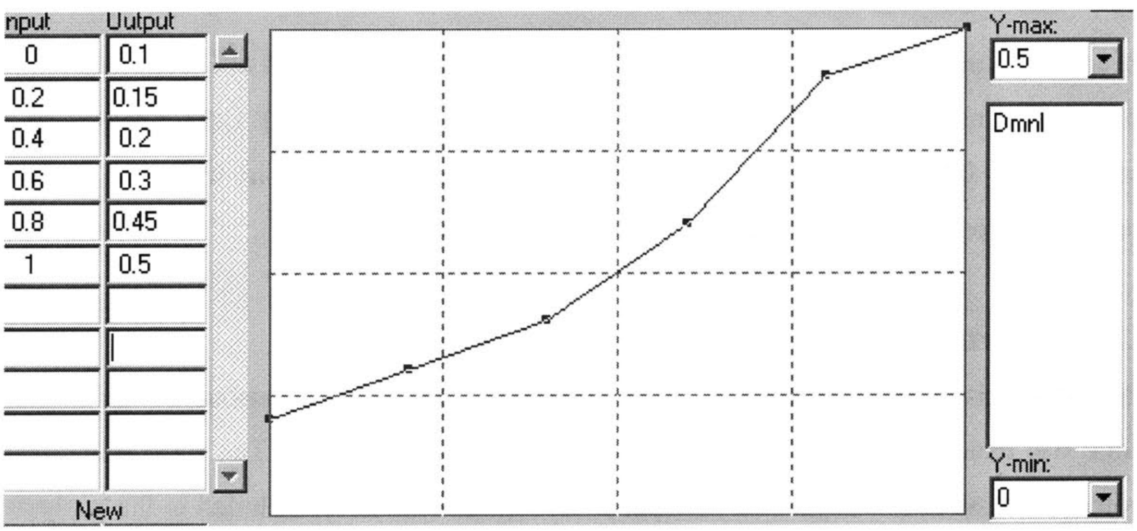


Figure 6.8 Efficiency V.S. Manpower

All delays in this analysis are defined as the first-order delay as expressed in Equation 6. As Figure 6.9 shows, the outflow, *Released Design*, is the stock of design in transit, *Release*, divided by the average delay time, *Release Delay*.

$$\mathrm{Re}\,leasedDesign(t) = \mathrm{Re}\,lease(t) / \mathrm{Re}\,leaseDelay \qquad (6)$$

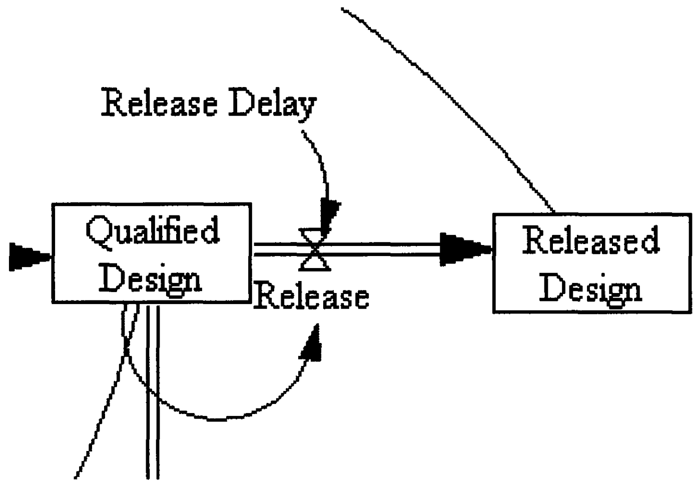


Figure 6.9 First-Order Delay

6.2 SD Analysis and Results

Three scenarios are analyzed in this research: 1) Uncertainty Analysis at Different Design Stages; 2) Uncertainty Analysis at the same design stage; and 3) Case Study – SD Analysis for OEM A Truck Project. The results are presented in terms of project completion, resources allocation, and cost of manpower.

6.2.1 Uncertainty Analysis at Different Design Stages

The analysis is focused on the effects of uncertainties occurring at various design stages. Table 6.1 lists the selected variables and their respective values. The total scheduled project duration is 180 days. No external uncertainties have been included in the analysis of the baseline model. All variables, except the external uncertainties, have been tuned to make the Baseline model to meet the project schedule, 180 days (see Appendix I). The project completion criterion is set at 99% of project work load. If the completion is more than 99%, the project is done. All the external uncertainty levels are intentionally set to 50% for the purpose of comparison. When uncertainty is 50%, there is 50% chance for engineering changes. The total staff level will be kept constant throughout the process, 8 people. No overtime or other additional resources are allowed in this SD model analysis.

Table 6.1 Variable List for SD Analysis

Model Name	External Uncertainty 1	External Uncertainty 2	External Uncertainty 3
BaseMdl	0	0	0
PK05	50%	0	0
Func05	0	50%	0
LT05	0	0	50%

External Uncertainty 1: Engineering Changes at Package Design stage
External Uncertainty 2: Engineering Changes at Function Design stage
External Uncertainty 3: Engineering Changes at Late Design stage

Figure 6.10, the analysis results from the SD model, is the curve of the Released Design in terms of time. After 180 days, the BaseMdl model, which does not have any uncertainties, is expected to complete the project on time. The PK05 model, which has 50% of engineering changes at the Package Design stage, is expected to complete 65% of design work only. The completed design work will be further reduced to 54% for the Func05 model and 53% for the LT05 model. The Func05 model and the LT05 have 50% of engineering changes at each respective stage as listed in Table 6.1.

The package design stage (PK05) has normally the most engineering activities (100% of all activities), the functional design stage (Func05) will still have some remaining activities (about 30% of all activities), and the final stage (LT05) will only have a limited number of activities (less than 5%). Based on the completion percentages of three cases (PK05 65%, Func05 54% and LT05 53%), it can be found that:

1. The 35% (PK05) delay is caused by 50% of all activities;
2. The 46% (Func05) delay is caused by 15% of all activities;
3. The 47% (LT05) delay is caused by 2-3% of all activities.

It is clearly shown that the later the engineering changes occur, the higher the impact on the project completion will be.

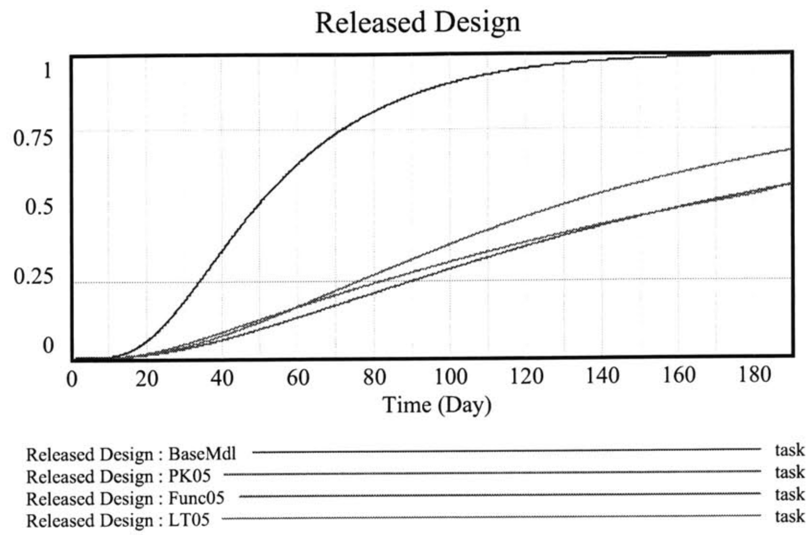


Figure 6.10 Released Design with Uncertainties at Different Stages

A close review of Figure 6.10 shows that the LT05 model has more projects completed during the first 50 days after kickoff of the project. This is due to the fact that no Package Design and Function Design uncertainty is set in the LT05 model. So the LT05 model shows a better performance at the beginning of the project. As the project keeps progressing, late engineering changes happen. These changes will put extra burden, design iterations, on the engineering design work in the late design stage. The design efficiency of the LT05 model will be lower than that of other models. Without additional resources, the project cannot be completed on time.

Figure 6.11 shows the staff level dedicated to the engineering design. The staff level for engineering design is in reverse proportion with respect to the fraction of project completed. Due to the priority of routine engineering service, all staff will be involved in design work at the beginning. As the completion time of the project is increased, some staff will be released to work on R&D research, Figure 6.12. Since no external uncertainty is included in the baseline model, there is less re-work in the whole process. The project can be completed much faster in the baseline model than other cases which have external uncertainties included. Therefore, more staff can be released from routine design work in the baseline model. Figure 6.11 shows that the staff level for routine engineering design with fewer external uncertainties is much lower than that with higher external uncertainties. Figure 6.12 shows more staff will be shifted to R&D activities if the uncertainty level is lower.

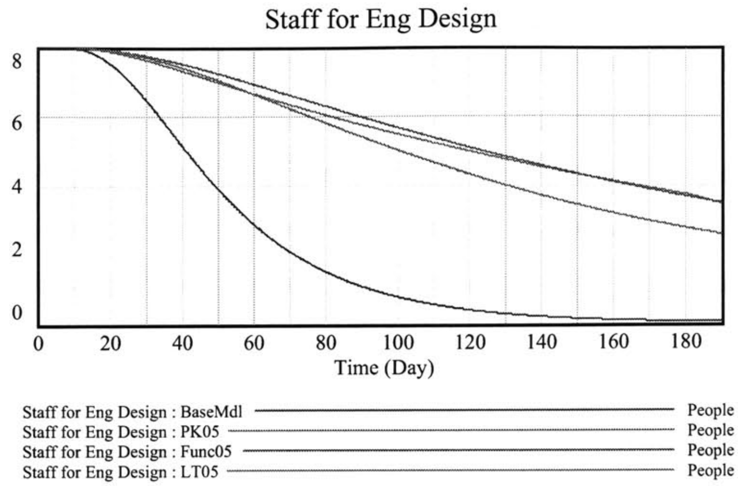


Figure 6.11 Staff for Engineering Design

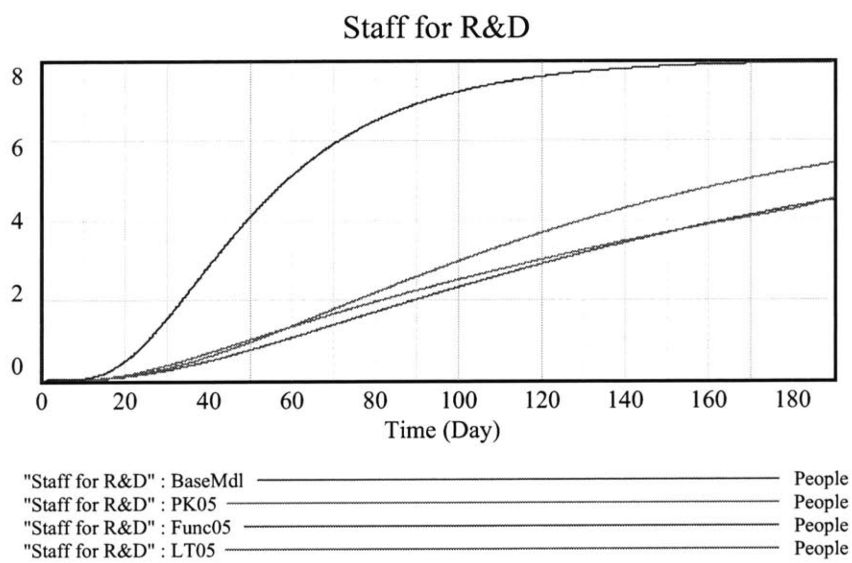


Figure 6.12 Staff for R&D Activities

The effects of the late engineering changes can also be found in both Figure 6.11 and Figure 6.12. The LT05 model needs less staff at the beginning of the project than the Func05 and the PK05 models. This is because the LT05 model has better performance at the beginning of project as shown in Figure 6.10. However, late engineering changes will change the scenario. Due to the slow performance of the LT05 model in the late design stage, more staff will be held in the engineering service later.

Figure 6.13 shows the total project cost in terms of manpower. The manpower is evaluated as the accumulated cost involved in the whole design process. The less-uncertainty there is, the less re-work will happen. Therefore, the baseline model has the lowest cost. The costs due to the uncertainties and engineering changes are extremely high for other cases. This SD model predicts that the cost induced by uncertainties can be twice as much as the scheduled cost is. Obviously, the later the changes happen, the higher the cost will be. Except for the baseline model, the cost presented in Figure 6.13 is only part of the total project cost. As shown in Figure 6.10, no model, except the baseline model, completes the project within 180 days. Therefore, for cases other than the baseline model, the total cost for the project to finish will be much higher.

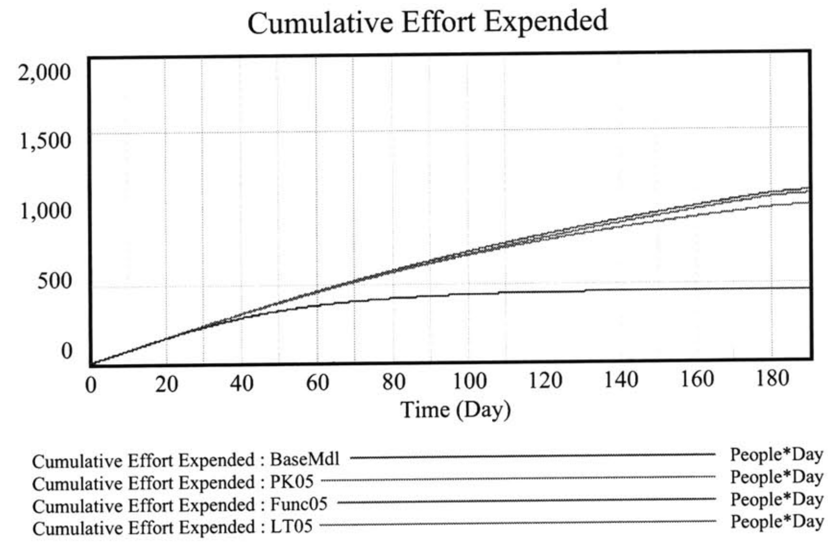


Figure 6.13 Cumulative Effort Expended

6.2.2 Uncertainty Analysis at the Same Design Stage

Based on the investigation and statistics, most of engineering changes are occurring at or before the Package Design stage. Compared with changes at the Package Design stage, the chance of late engineering changes is relatively low. The analysis in this section is focused on the cost due to engineering changes in the Package Design stage. Table 6.2 shows the model and variables used in this analysis.

Table 6.2Uncertainty Level in Package Design

Model Name	External Uncertainty in Package Design
BaseMdl	0
PK01	10%
PK03	30%
PK05	50%

Figure 6.14 shows the project completion under various uncertainty levels in the Package Design stage. As expected, the lower uncertain level has better performance. Table 6.3 shows the performance in terms of percentage of project completion within 180-day frame.

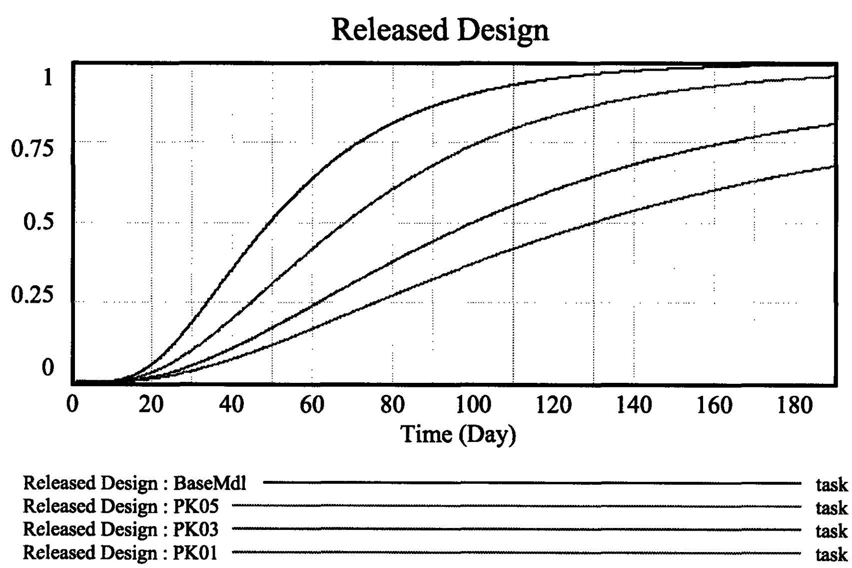
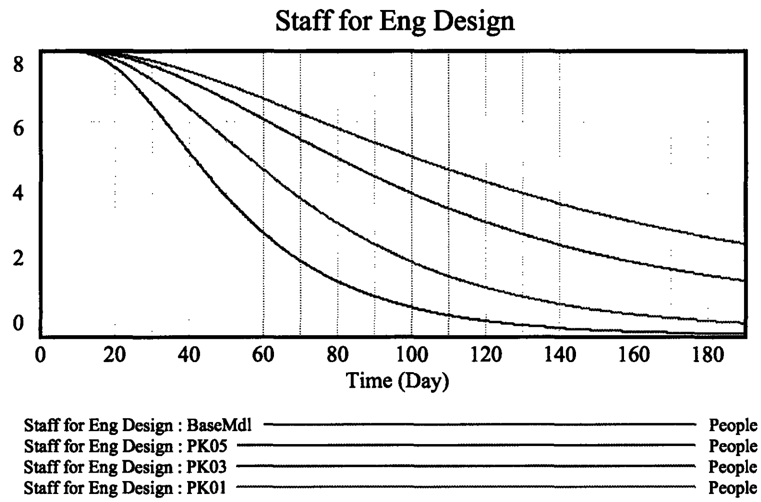


Figure 6.14 Project Status with Various Package Design Uncertainties

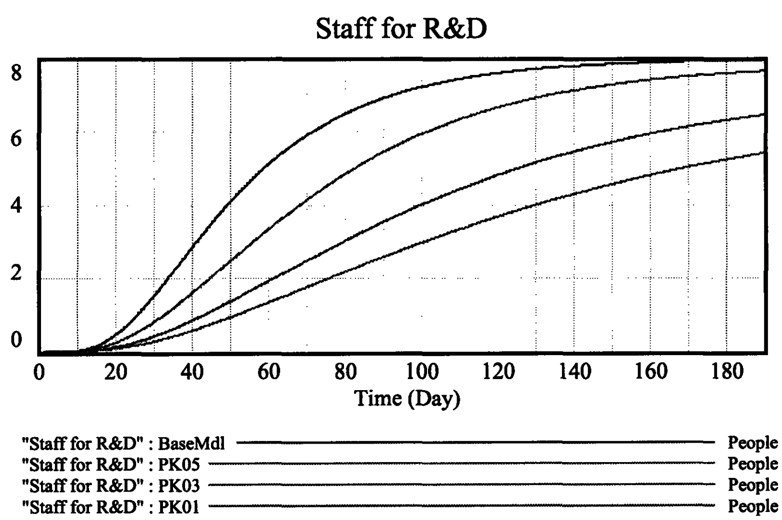
Table 6.3 Project Completion V.S. Package Design Uncertainties

Model Name	External Uncertainty in Package Design	Percentage of Project Completion
BaseMdl	0	100%
PK01	10%	95%
PK03	30%	79%
PK05	50%	65%

Figure 6.15 shows the staff allocation with respect to uncertainties in the Package Design stage. The lower uncertainties require less manpower to complete the project and have more free resources to dedicate to the R&D activities. The lesser manpower involvement will have less cost as shown in Figure 6.16. Assume the cost of the baseline model is the budget. When the uncertainty factor is 10%, the cost at 180th day is 38% over that budget with 95% of project completion. When the uncertainty factor is increased to 50%, the cost at 180th day is 218% over the budget with only 65% of project completed.



(a) Staffs Dedicated to Engineering Design



(b) Staffs Dedicated to R&D Activities

Figure 6.15 Staff Allocation V.S. Package Design Uncertainties

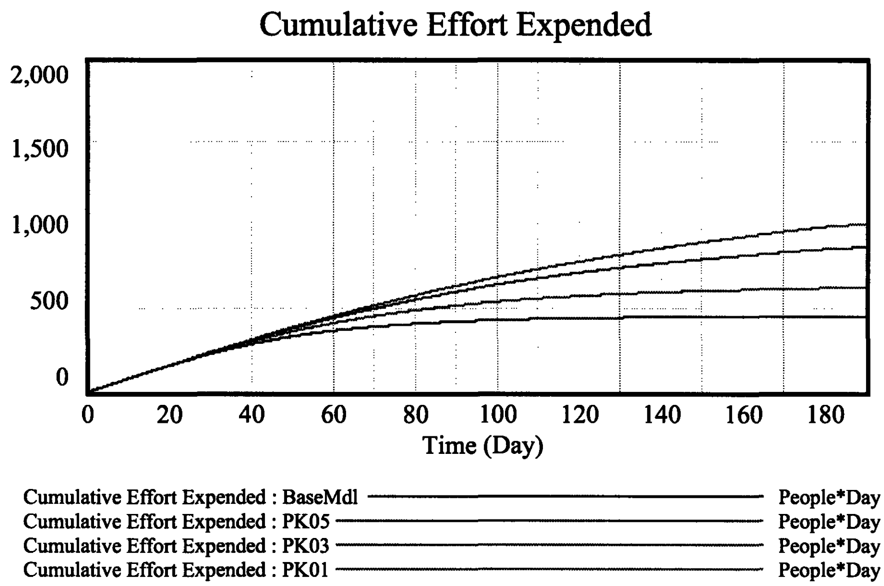


Figure 6.16 Cumulative Efforts V.S. Package Design Uncertainties

6.2.3 Case Study - SD Analysis for OEM A Truck Project

This analysis follows an OEM A truck project. The uncertainty levels are set as 10% at the Package Design stage, 5% at the Function Design stage, and 1% at the Late Engineering stage. Total development cycle of this project is 1080 days, 36 months. The model is developed based on the process of one platform only; the process includes all steps illustrated in Figure 6.1. The schedule time of platform development is 560 days. The analysis result is titled as "Case." For comparison purpose, a reference model which does not have any uncertainties is also developed. Its analysis result is titled as BaseMdl2. Figure 6.17 shows the analysis results in terms of the design releasing. Even with various uncertainties, the Case model can still complete the project on time as well as the reference model does. Due to the lower uncertainty level, the reference model has better efficiency than the Case model does. The task completion percentage of the reference model at a specific time is always higher than that of the Case model.

The lower efficiency of the Case model can be further proved by the total effort expended, Figure 6.18. Total expended manpower of the Case model is 45% higher than the reference model. This 45% overrun of manpower is due to external uncertainties in the process. Even though the uncertainty does not affect the completion of project, extra cost due to uncertainties is very high. Usually, the supplier has to absorb these extra costs.

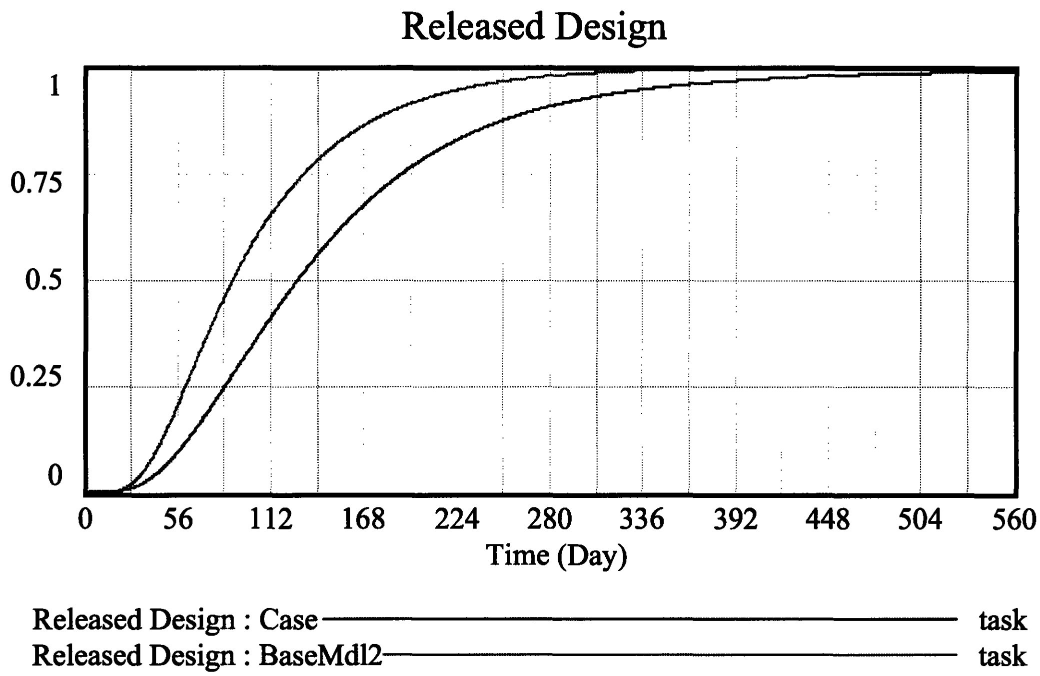


Figure 6.17 Project Completion

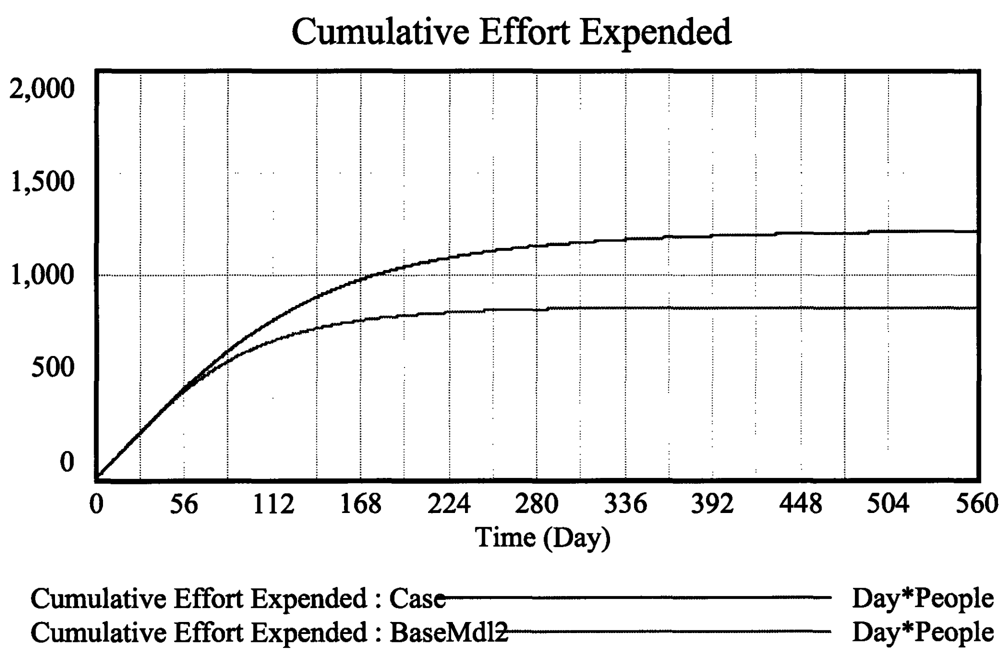


Figure 6.18 Engineering Cost

Figure 6.19 shows the allocation of staff. The uncertainties in the Case model reduce the efficiency compared with that of the reference model. As a result, the Case model will hold more manpower during the whole process. This result is in agreement with the results presented in Figure 6.18. The uncertainties in the process not only increase the engineering cost, but also heavily constrain the allocation of resources.

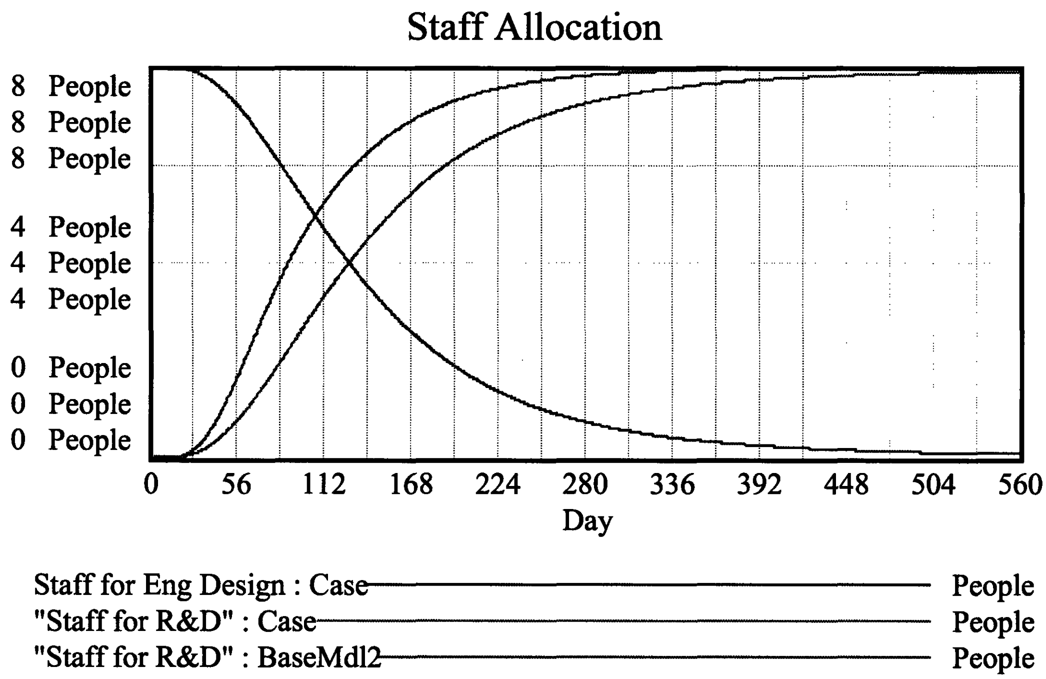


Figure 6.19 Staff Allocation

6.3 Conclusions from SD Analysis

The SD model reveals and quantifies the extra engineering costs due to uncertainties at various design stages. The analysis results show the damage to the engineering operation due to external uncertainties. The higher uncertainty level or the later uncertainties will cause a huge budget overrun; for example, 50% of early design uncertainty will bring in more than 200% of budget overrun. No company can survive such a situation. The uncertainty induced re-works are all considered as wastes in lean engineering practice.

The analysis also shows that a large portion of manpower will be bundled to routine engineering design work when the uncertainty level is high. In order to meet the design deadline, the management has to put all available resources into routine engineering design business. The R&D activities will be put into a secondary place under this firefighting mode. Eventually, this will damage the development of company competency. A company without competency does not have a future. In the view of company development, uncertainties in the whole engineering process must be removed.

To practice lean engineering, the removal of uncertainties can never be over-emphasized. This SD model is an effective tool to analyze the ArvinMeritor ET engineering process. This tool can be used at different stages of project management:

1. Project preparation: Before the project is kicked off, this SD model can provide a reference for determining the project buffer based on previous experience. This buffer can be considered as process time. The buffer can effectively reduce the extra cost due to uncertainties during the process;
2. Project procession: During the project process, this SD model can be used as a prediction reference. If the uncertainty level is different from the prediction in the project schedule, the SD model prediction can provide an effective reference to management in terms of budget overrun. The management can decide on the proper firefighting action, such as hiring more experienced staff or allowing overtime to catch up on the schedule;
3. Project conclusion: After the project is completed, this SD model can be reviewed based on the process project. The model may need to be calibrated for better process prediction. The improved prediction would be a better reference for future project schedule development.

Furthermore, the SD results provide a better communication base between OEMs and suppliers. Both sides will have a quick access to evaluate the cost of engineering changes during the process. It will greatly facilitate a better project coordination in management and design. And better coordination will eventually reduce the external uncertainty level, which is beyond the control of ArvinMeritor.

Chapter 7 Conclusion & Recommendation

This research has explored the lean engineering techniques in the automotive industry. Various lean engineering practices have been evaluated for the exhaust industry. The value stream of engineering service in ArvinMeritor ET division has been mapped. Both internal and external uncertainties have been studied and their sources have been identified. The interrelation between the uncertainties and process iteration has been defined. It is realized that engineering changes are the major sources of the uncertainties within the ET division. The DSM technique has been used to optimize the current engineering process, and SD analysis can be used to quantify the effect of uncertainty in the current engineering process.

A DSM model has been developed based on the map of the ET engineering value stream. The HoQ prioritized the various engineering procedures to identify the important processes based on their added values. Based on the HoQ results, the DSM analysis successfully identified the most critical steps and the latent bottleneck iterations in the engineering service process. The process uncertainties in terms of duration, probability, impact, and learning curves can be evaluated and compared with suggested excel macros. An improved engineering process for engineering service has been proposed. The appropriate management strategies to improve the engineering process have been also provided. The new engineering process will be more robust to the engineering changes and can greatly cut the lead time of the PD process.

An SD model revealed and quantified the effects of uncertainties and engineering changes for the generalized current engineering process. The SD results clearly indicated the unpredictable engineering dynamics, which caused a budget overrun, project delay, and firefighting for resources. The external uncertainties are beyond the control of ET. To effectively reduce the re-work and firefighting events, better project coordination between OEMs and suppliers is required. The SD analysis results will facilitate a mutual understanding between OEMs and suppliers.

The research has provided a general systematic approach for lean engineering practice and system project management. The research results have demonstrated that the combination of VSM, DSM, HoQ, and SD is an effective approach to managing the exhaust engineering process.

The suggested approach can be modified and expanded for other applications. The corresponding inputs and assumptions need to be applied. Other project management tools can be selected for different applications.

Appendix I

Variable	Unit	Expression or Initial Value
Project Granted	task	1
Package Design	task	Rework on Package-Package Design Iteration-Completed Package
Completed Package	task/day	Package Design / Package Design Delay
Package Design Iteration	task/day	Package Design * Internal Uncertainty Level
Undiscovered Re-package Design	task	Package Design Iteration + Package Change – Rework on Package
Package Design Delay	day	10*(1-Effection on Design Efficiency)
Rework on Package	task/day	Undiscovered Re-package design/Re-Eng Time on Package * Completed Project
Re-Eng Time on Package	day	5
Package Change	task/day	Completed Package Design * External Uncertainty Package / Time Step
External Uncertainty Package	Dmnl*	0
Completed Package Design	task	Completed Package – Package Change – Package Info
Info Delay	task/day	5
Function Design	task	Rework on Function + Rework due to late Eng Change – Function Design Iteration – Completed Function
Completed Function	task/day	Function Design / Function Design Delay
Function Design Delay	day	5*(1-Effection on Design Efficiency)
Function Design Iteration	task/day	Function Design * Iteration Uncertainty Level
Undiscovered Function Rework	task	Function Design Iteration + Functional Changes – Rework on Function
Rework on Function	task/day	Undiscovered Function Rework / Re-Eng Time on Function * Completed Project
Re-Eng Time on Function	day	5
Functional Changes	task/day	Completed Function Design * External Uncertainty Function / Time Step
External Uncertainty Function	Dmnl	0
Completed Function Design	task	Completed Function – Functional Changes - Prototype

Appendix I (continue)

Variable	Unit	Expression or Initial Value
Prototype	task/day	Completed Function Design / Prototyping
Prototyping	day	10
Product Testing	task	Prototype - Test
Test	task/day	Product Testing / Test Duration
Test Duration	day	30
Qualified Design	task	Test – Rework due to late Eng Change-Release
Re-work due to late Eng Change	task/day	Qualified Design * External Uncertainty Late Eng Change * Completed Project / Time Step
Project Finished Based on Task	Dmnl	IF THEN(Qualified Design>Fraction Complete to Finish * Project Granted, 0,1)
Fraction Complete to Finish	Fraction	0.99
Completed Project	Dmnl	Project Finished Based on Task * Switch for Finish Based on Task + (1-Switch for Finish Based on Task) * Project Finished Base on Schedule
Switch for Finish Based on Task	Dmnl	IF THEN ELSE (Fraction of Project Completion < 0.99, Fraction of Project Completion, 1)
Project Finished Based on Schedule	Dmnl	IF THEN ELSE (Time>Scheduled Completion Date, 0, 1)
Scheduled Completion Date	day	180
Effort Expended	People*day	Staff for Eng Design * Completed Project
Cumulative Effort Expended	People*day	Effort Expended
Total Staff	People	8
Staff for R&D	People	Total Staff* Fraction of Staff Resources to Eng Design
Staff for Eng Design	People	Total Staff * (1- Fraction of Staff Resources to Eng Design)
Fraction of Staff Resources to Eng Design	Fraction	IF Then Else (Time>0, Fraction of Project Completion, 0.5)
Fraction of Project Completion	Fraction	Released Design / Project Granted
Fraction of Engineering Efforts	Fraction	IF Then Else (Time>0, Cumulative Effort Expended / (Cumulative Effort Expended + Effort in R&D), 0.1)
R & D Load	Dmnl	1

Appendix I (continue)

Variable	Unit	Expression or Initial Value
Efforts in R&D	People*day	Effort of R&D
Effort of R&D	People	R&D Load * Staff for R&D
Intern Uncertainty	1/day	1
Internal Uncertainty Level	1/day	Internal Uncertainty* (1 – Engineering Quality)
Table for Effort on Quality	Dmnl	Lookup Curve
Effect on Design Efficiency	Dmnl	Table for Design Efficiency(Fraction of Engineering Efforts)
Release Delay	Day	2
Release	task/Day	Qualified Design / Release Day
Released Design	task	Release

*: Dmnl: Dimensionless

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